Duel (Revisited): A Networked Implementation of Xenakis's Game Piece

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Abstract

In this article, Xenakis's game of musical strategy *Duel* is examined and re-implemented as a computer-aided system for networked music performances. Motivated by an analysis revealing inconsistencies between game-theoretical formalisms and their translation to a game piece under Xenakis's interpretation, this work draws from the conflict between rational (assumed by game theory) and natural (driven by aesthetic preferences) behaviours. The revisited *Duel* highlights said conflict by design, because it comprises two principal modules: one simulating the conductors' decision-making, the other modelling the corresponding sonic events, originally performed by orchestras. Although the latter can be automatically rendered using predefined algorithmic processes, these are meant to be edited, mediated, or even entirely replaced in real time by live coders. This article provides a detailed description of the main author's system, describes the specifics of its premiere, and offers a reflection around the aesthetics of musical systems based on game theory, caught in the struggle between rational policies (to maximise rewards) and pleasing (but mathematically suboptimal) musical results.

Keywords: Networked music performance, game pieces, live coding, Xenakis.

1 Introduction

The system described in this article sits at the intersection of different theories and disciplines of practice, presenting itself not only as a (live) music performance or composition tool, but also as an opportunity to investigate decision-making under uncertainty from perspectives driven by sometimes conflicting objectives.

From a technological viewpoint, the system lends itself to explorations in the realm of algorithmic composition and human-machine interaction, including more recent modalities of performance, such as live coding. The system's internal structure – comprising separate modules that communicate either locally (e.g., they all run on a single local host, or on co-located hosts) or remotely (e.g., modules run off-site, in separate locations) – makes it also particularly suited for networked music performances. While the system might inherit aesthetic hues from all these different areas of techno-performative practices, its foundational aim of modular openness leaves it devoid of strict categorisations and confers on it a composite, if blurred, aesthetic identity.

From a theoretical perspective, on the other hand, the system is based on game-theoretical axioms, embodying what Xenakis calls *heteronomous music*, which introduces a "concept of external conflict" and a "complement of dialectical structure" into stochastic music (Xenakis, 1992, pp. 111–112). To clarify, for Xenakis, *internal conflict* relates to the intrinsic quest for aesthetic integrity on behalf of the composer, whereas *external conflict* concerns the dynamics generated by opposing orchestras or instrumentalists/players. Kalonaris (2022) argues that the tension between internal and external conflict is perhaps the most defining characteristic of Xenakis's games of musical strategy.

Kalonaris (2022) also argues that the true value of employing a game-theoretical model to inform real-time interactions between conductors and orchestras is the affordance to subvert its axioms, whenever aesthetic and musical imperatives dictate it. Xenakis was clearly aware of the aesthetic and social dimension of game theory when he informs us that he had "been interested in social questions, in the relationship between people and the aesthetic aspect of all that" (Varga, 2003, p.49).

To better understand the inner workings of the system presented in this article, brief definitions are in order.

Networked music performance, hereinafter "NMP", is a mode of musical interaction originated in the late 1970s through the experiments of the League of Automatic Music Composers, whereby musicians interact with one another over a computer network. There have been different definitions for NMP, some emphasising the limitations of the technical constraints (e.g., latency), others embracing them in an effort to explore other perspectives on disembodied presence. For an in-depth review of NMP, the reader is referred to Gabrielli and Squartini (2015).

Live coding involves creating and executing code in real time to generate music, often during a performance, allowing for spontaneous composition and improvisation. An important notion in this context is *liveness* in programming, which Tanimoto (2013) defines as the capacity to modify and update a program while it is running. A closely related concept is that of *algorithmic agency* (Rutz, 2016), which is understood as "the outcome of the mutual human-machine incursions expressed in the writing process" (Xambó & Roma, 2024).

Game theory is a branch of applied mathematics that studies conflict or cooperation among agents or coalitions. It assumes rational agents and it models their interaction on the basis of behavioural strategies aimed at maximising one's (or one's coalition's) rewards. Game theory is normally employed in economics and social network theory, but it is also applied in computer and systems science. A basic understanding of game theory's axioms is hereinafter assumed, but an essential compendium of terminology and fundamental notions is provided for the reader in the Appendix.

Game pieces Cox and Warner (2004) and Havryliv and Vergara-Richards (2006), on the other hand, are generally intended as systemic musical works where the affordances of the players/performers are bounded by pre-established rules of conduct, and are often associated with improvisational practices. Game pieces need not include game-theoretical formalisms. In fact, they more often draw from notions of *game* developed in sociology and anthropology (Caillois, 1961; Huizinga, 1955), as in the case of Mathius Shadow-Sky's works (e.g., *Ludus Musicae Temporarium*) or John Zorn's series of pieces (Brackett, 2010) inspired by table-top war games (e.g., *Cobra*) and sports (e.g., *Lacrosse* and *Hockey*). At other times, these pieces may instead be inspired by game design (Tekinbaş & Zimmerman, 2003), as with Havryliv's works (Havryliv & Vergara-Richards, 2006).

Few attempts have been made formally to map formal games of strategy (i.e., as defined in game theory) to game pieces. Besides some sporadic experiments with Bayesian games and probabilistic graphical models (Kalonaris, 2016, 2018), the most notable examples are three pieces by Xenakis: *Duel* (1959), *Stratégie* (1962) and *Linaia-Agon* (1972). Of these, the first is chosen as the template for a prototypical system whose capacities range from fully automated (machine-machine) to co-creative and/or collaborative (human-machine).

1.1 Related Work

Relevant precedents for technologically mediated renditions or analyses of Xenakis's game piece trilogy include the version of *Linaia-Agon* by Benny Sluchin, documented in a DVD (Sluchin, 2015) with original radio broadcasts and newly recorded live and studio performances of the piece using a computational interface. *Linaia-Agon* has also been analysed by DeLio (1987), Sluchin (2005), and Beguš (2016). As for *Duel*, an interactive version in the form of a live installation was realised by Liuni and Morelli (2006) giving members of the audience the role of conductors and using their movements to drive the score, by means of computer vision algorithmic analysis. The score was also rendered in real time on a large screen. In Liuni and Morelli's (2006) version of *Duel*, the musical output was obtained using playback and processing of audio samples (i.e., with no live orchestras). *Duel*'s game dynamics were also modelled and analysed by Sluchin and Malt (2011) by simulation, using four different methods for selecting tactics. This work, as well as a follow-up study (Sluchin & Malt, 2024), do not seem to be accompanied by live performances or recordings, to the authors' knowledge.

Before delving into the specifics of the version of *Duel* presented in this article (see Section 3), it is important first to describe Xenakis's original work.

2 *Duel*

Duel is fully described in Chapter IV of *Formalized music* (Xenakis, 1992). It is modelled as a formal game, thus as "a description of strategic interaction that includes the constraints on the actions that the players can take and the players' interests, but does not specify the actions that the players do take" (Osborne & Rubinstein, 1994, p.2). In particular, *Duel* is a *zero-sum game* with *complete* and *perfect information*, which means that players are aware of their opponent's action history, and one player's gains are the other's losses. Practically, this piece sees two conductors (hereinafter x and y) competing against each other via corresponding (musical) events/tactics that they dictate to their respective orchestras, in accordance with combinations of pairwise actions (i.e., the payoff matrix) associated with an aesthetic outcome value stipulated by the composer.

Table 1: *Duel*'s payoff matrix and associated weights of the mixed strategies.
Alt text: Table of the rewards corresponding to pairs of actions taken by conductors x and y, complete with the solution of the mixed strategies equilibrium expressed as a ratio, for each combination.

		y						
		I	II	III	IV	V	VI	
x	I	-1	+1	+3	-1	+1	-1	$\frac{14}{56}$
	II	+1	-1	-1	-1	+1	-1	$\frac{6}{56}$
	III	+3	-1	-3	+5	+1	-3	$\frac{6}{56}$
	IV	-1	+3	+3	-1	-1	-1	$\frac{6}{56}$
	V	+1	-1	+1	+1	-1	-1	$\frac{8}{56}$
	VI	-1	-1	-3	-1	-1	+3	$\frac{16}{56}$
		$\frac{19}{56}$	$\frac{7}{56}$	$\frac{6}{56}$	$\frac{1}{56}$	$\frac{7}{56}$	$\frac{16}{56}$	

In Xenakis's original description of *Duel*, the *payoff matrix* undergoes several transformations to ensure a fair game, and its final form is shown in Table 1. For each cell in the matrix, payoffs are expressed as a single signed integer, because they are symmetrical (opposites); for example, a -1 means $(-1, 1)$ where the first value in the tuple would be assigned to x and the second to y. The *mixed strategies Nash equilibrium* for *Duel* can be calculated by determining the probability corresponding to each strategy so that x is indifferent to the actions of y, and vice versa. That is, each conductor selects the next event based purely on these probabilistic weights. For example, x will pick event I with a probability of $\frac{14}{56}$ and so forth. Tactics corresponds to different musical events, listed below:

- I: Cluster of sonic grains[1]
- II: Parallel sustained strings with fluctuations
- III: Networks of intertwined string glissandi
- IV: Stochastic percussion sounds
- V: Stochastic wind instrument sounds
- VI: Silence

To understand the main sources of inspiration for the authors' revised version of *Duel*, two important aspects relating to its original formulation must be addressed: one concerns the disparity between the theoretical game type defined by Xenakis and how this is effectively enacted/translated in practice; the other concerns two diverging but concurrent notions of *best response* in a typical performance of *Duel*, one based on rationality/mathematics, the other on aesthetics.

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[1] For example, pizzicati, blows with the wooden part of the bow, very brief arco sounds distributed stochastically.

2.1 Game Formalism

Firstly, it is important to clear some of the confusion around the nature of *Duel*'s game model. Xenakis claims this to be a synchronous game but, in the same breath, his instructions outline the opposite, pointing at a sequential order in the decisions taken by the conductors. To this end, it has been shown (Kalonaris, 2022) that *Duel* is a finitely repeated sequential game with perfect and complete information, or, more succinctly, a *finitely repeated extensive game*. Examples of contradicting messages in the original description of *Duel* (and/or *Stratégie*) are statements such as "couples of simultaneous events" (Xenakis, 1992, p.114) and "pairs of tactics are performed simultaneously" (Xenakis, 1992, p.126), which need to be somehow reconciled with "deciding who starts the game is determined by a second toss" (Xenakis, 1992, p.126) (the first toss having been used to decide who is x and who is y), or with Figure IV-4 (Xenakis, 1992, p.126), reproduced here in Figure 1, where the alternate sequence of tactics is evident.

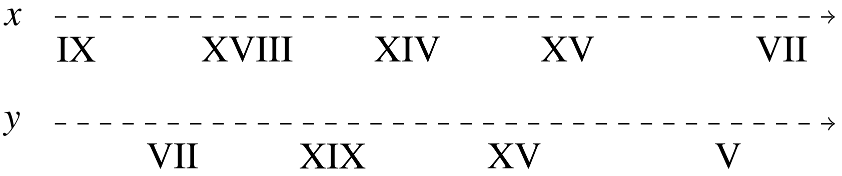

Figure 1: A reproduction of Xenakis's original Figure IV-4 in *Formalized music*. Note: in this version, only the temporal sequence of tactics is displayed, whereas corresponding payoffs are omitted.
Alt text: Two parallel directional lines for conductor x and y with markings (below) of the temporal sequence of the (hypothetical) tactics chosen by each.

2.2 Decision-Making

The role of human decision-making processes beyond mathematical abstractions is central if one is to have a more comprehensive discussion around the aesthetics of (musical) games. Although in this article a "game" is defined according to a game-theoretical perspective (see the Appendix for a formal definition), it is important at this point to consider (albeit briefly) different viewpoints rooted in sociology, anthropology, and game design, among others. For example, game designer Cook (2007) argues that "to accurately describe games, we need a working psychological model of the player". Game theory might only offer somewhat impoverished player profiles, because intrinsic or emerging traits such as excitement, inventiveness, subversion, etc., must be subsumed by mere calculation and rational thinking.

Kalonaris (2022) has shown that if agents were purely to follow the axioms of rational decision-making when selecting strategies during a *Duel*, the musical contrast or variety would suffer. This is because rational agents would eventually learn optimal behaviours and best responses, that would manifest in playing the same strategy over many consecutive rounds of the game. This was verified by running a tournament involving three computational conductors: two were modelled using Reinforcement Learning, a flavour of machine learning where an agent takes an action in a given environment, receives a corresponding reward, and adjusts the subsequent action to maximise said payoff. The third conductor, by contrast, would not learn but would choose at random. Both types lead to undesirable musical outcomes, i.e., to too little or too much contrast.

By contrast, human conductors might be arguably more interested in music than mathematics. It is also perhaps as unreasonable to expect proficiency in calculating Nash equilibria or performing backward induction as it is to expect chaotic and random-like decisions that are not backed by musical agendas. It is more likely that their decision-making process could be equally informed by their aesthetic preference and musical judgement (e.g., how does their next strategy complement or contrast with their opponent's current one), as it is by Xenakis's instructions.

Xenakis's *Duel* thus embodies not only the conflict between players in a zero-sum game of strategy, but also the intrinsic tension between the mathematical process of optimisation required to "win" (i.e., choosing the *best response*) and the musical process involving aesthetic and artistic integrity/ consistency (i.e., choosing the most appropriate musical complement). That is, each conductor may in fact have to choose between numerically and musically suboptimal results.

The problematic aspects of the original game piece as discussed above provided the main author with the impetus for the design and implementation of the *Duel* version presented in this article, hereinafter *Duel Revisited*. In particular, the main author (i.e., the system designer) wanted formally to address these factors in the specifications of the system rather than leaving them to the judgement or inclination/predisposition of the conductors as in the original game piece. How this was done is explained in the next section.

3 *Duel Revisited*

Duel Revisited is designed to comprise two independent modules. One addresses everything concerning the game specifications and the decision-making for choosing strategies. The other is responsible for the musical rendition of the tactic pairs. This enables one to keep *Duel Revisited* sound-agnostic and sufficiently flexible to accommodate a range of performance case scenarios or sound-generation approaches and technologies. For example, *Duel Revisited* can run on a single local machine, or it can be used in a networked performance (either co-located or remote). Orchestras can be as simple as an algorithmic rendition of the musical tactics, ensembles of live coders interpreting Xenakis's musical instructions, or even full orchestras executing Xenakis's original score following the virtual direction of their computational directors. For practical reasons, the two independent modules will henceforth be referred to as *Score* and *Sound*. Note the capitalisation, particularly in the case of Score, to disambiguate this from the term indicating the numerical value of the accumulated points for a given conductor/player.

3.1 Score

This is the central control unit responsible for spawning the conductors, and all other structural decisions relating to the unfolding of the game. This module is implemented using the Python programming language,[2] and is in charge of the following game specifications.

3.1.1 Matrix

In *Duel Revisited*, the matrix object loads the game matrix as specified in Section 2 and calculates the mixed strategy Nash equilibrium. As seen, the solution has already been provided by the composer, but one could load a different two-player game matrix if desired. In that case, the equilibrium is calculated using the *nashpy* library,[3] according to different methods, such as *vertex enumeration* or the Lemke and Howson (1964) method. For this particular iteration of the system, the equilibrium is solved via *support enumeration* (von Stengel, 2007). The matrix class can then be queried by other modules to return the payoffs for a given pair of actions.

3.1.2 Node

Rather than choosing exclusively one (synchronous) or the other (sequential) time model, and to integrate the axiomatic wishes of Xenakis with the historical practice when performing his work, *Duel Revisited* has a dedicated object that randomly selects either a synchronous or a sequential decision node, based on a probability p specified by the user who instantiates and runs the system. The default value is $\frac{1}{2}$. If conductors were human, synchronous decision-making could be enforced by specifying the exact times, e.g., using a counter/timer, and/or at intervals decided by the composer or the conductors. Xenakis, however, only discusses user interfaces for choosing tactics and/or awarding points (more on this later). The decision node object thus offers a way to enhance coordination between the two (virtual) conductors and seemed a useful addition to the game's specifications.

3.1.3 Conductor

Conductors are modelled as simple agents. A conductor C can have a *personality* $P \in \{\mathit{rational}, \mathit{conservative}, \mathit{opportunist}\}$ which is mapped to {mixed strategies, minimax, maximax} via non-zero, normalised scaling coefficients. For example, a rational conductor will have a strategy weights profile $S = [\alpha\cdot \text{ mixed strategies}, \beta\cdot \text{ minimax}, \gamma\cdot \text{ maximax }]$, where $\alpha, \beta, \gamma \neq 0$, $\alpha > \beta$, $\alpha > \gamma$,

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[2] https://python.org/.

[3] https://pypi.org/project/nashpy/.

and $\alpha + \beta + \gamma = 1$. The mixed strategy is simply a probabilistic weighted pooling, whereas minimax and maximax are implemented via matrix lookup. In the latter case, when faced with having to break ties for equal payoffs, C will do so by means of its *aesthetic preference* profile A, which is assigned at instantiation, randomly. Just like S, this is a normalised weighted distribution over the six possible musical events. For each decision node, the available events are re-scaled accordingly based on the original distribution. For example, let us assume that C_y is *opportunist* and having to respond to event I played by C_x. Under P_y, there are three available and equivalent actions: I, IV, and VI. Let us assume that C_y has an $A_y = [0.1875, 0.125, 0.125, 0.375, 0.125, 0.0625]$. The tie will be resolved by randomly choosing I, IV, and VI according to the following probabilities, respectively: $[0.3, 0.6, 0.1]$ (this is the normalised distribution for [0.1875, 0.375, 0.0625]). Once the conductor has chosen a strategy, it communicates this information to its orchestra via means of the Open Sound Control (OSC) protocol.[4]

3.1.4 Game

The game object ties all the above together in that it takes as arguments a matrix, a node, two conductors, and the lower and upper time bounds for any given event. If the node yields a sequential play, the game object first determines at random whether x or y act first. Subsequently the game object waits for a time length between $\frac{1}{4}$ and $\frac{1}{2}$ of the total event duration before asking the other conductor to act accordingly. Otherwise, if the node is synchronous, both conductors pick a strategy at the same time. The game logs the event's data in a history dataframe. In particular, it saves the game ID, the node type, the event total duration, the (eventual) time offsets for x and y, the actions taken by them, and their payoffs (for any given action pair).

3.1.5 Duel

This object is not strictly under the Score module, because it is exposed to the user and it is the main script that one uses to start the system. It takes care of all the piece's specification and it is run via the command line, passing fundamental arguments that can be modified to experiment with different settings, such as:

- **Event Pair Duration**: the system determines how long a given event pair continues for, by randomly selecting a time duration between a lower and an upper time boundary, provided as arguments at initiation time by the user. In the original work, Xenakis only suggests the lower bound (i.e., 10s), leaving the upper undetermined and subject to the conductor's wishes.
- **Piece Duration**: Xenakis suggests that the length of the piece can be determined in three ways. It can be conditioned on an agreed number of engagements (event pairs), on a time-out value (e.g., constrains due to a festival's time schedule, etc.), or it can be stopped when the sum of the payoffs for one of the conductors is equal to or greater than a stipulated "winning" value. Given the payoffs in *Duel*'s game matrix, and given that it is a zero-sum game, the third option does not heuristically lead to reasonable lengths. Therefore, *Duel Revisited* keeps only the first two options available, as a hyper-parameter entered by the user prior to commencing the performance of the piece.

As for the points calculation, every time a new game event is yielded, the system automatically adds the corresponding payoff to a conductor's count. There is arguably little value in announcing a "winner" among two automatic conductors, other than for adding dramatic effect. While the contest/conflict factor is what informs the inner mechanics of the system, the final outcome could well be omitted from explicit representation. Nevertheless, the duel object prints the outcome in any case.

3.2 Sound

This module is implemented using *SuperCollider*,[5] a popular audio synthesis programming environment used in sound design, algorithmic composition, and live coding. The main object of this

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[4] https://opensoundcontrol.stanford.edu/.

[5] https://supercollider.github.io/.

module is the orchestra, which receives OSC messages from the corresponding conductor, and realises musical directives accordingly.

3.2.1 Orchestra

As of the time of writing, the orchestra object is rather rudimentary, providing only basic templates of sample-based patterns using granular synthesis, one for each event/tactic in Xenakis's original piece. Nevertheless, Xenakis's original score was carefully studied for inspiration and to guarantee a sufficient level of conformity with the aesthetic objectives of the composer. Thus, the samples used for the Synths' input audio buffers reflect the description provided in *Formalized music* so that, for example, the pattern corresponding to event III will load and use a sample of string glissandi, and so forth. To differentiate between the same type of musical event, the two orchestras have a slightly different parametric domain, as well as being panned in the stereo field. The idea for this module is to make it as modular as possible so that, for different occasions/performances, it can be entirely replaced. More specifically, the role of orchestras can be taken by live coders or more sophisticated drop-in generative modules. Decisions on this front are case-specific, as shown in the next section, describing the premiere of *Duel Revisited*.

4 Performance

Duel Revisited was premiered at the Xenakis Networked Performance Marathon 2022 (XNMP22)[6] as part of Meta-Xenakis,[7] organised to celebrate the centenary of the composer's birth. The event ran continuously from 19:00 of the starting day until 03:30 of the following day (except for two 30-minute breaks to allow for stage changes and refreshments). It featured participants from ten different countries, who performed their works remotely with simultaneous participation of other remote and/or on-site artists, connected via the internet. The physical venue for the public performances was the Athens Conservatoire, and the audience comprised both the general public and the performers (including dancers) who contributed to the concert. Regarding *Duel Revisited*, the two orchestras were operated by two live coders associated with running the event. These two performers had previously collaborated in the context of the Athens local node of the Toplap "franchise",[8] although they had not had experience with adapting existing works in the manner of the authors' rendition of Xenakis's piece. The event was broadcast live and it is difficult to know exactly how many people attended beyond the participants who were physically present at the concert venue. By the same token, it is also challenging to infer with certainty a precise demographic for the attendees. However, despite the lack of hard evidence in this respect, and given the strong denomination of the event (i.e., a networked performance marathon), it seems reasonable to assume that most attendees were familiar or involved with the music-expressive niche of computer-assisted experimental and telematic music. This event was not, however, an "algorave", but more akin to a formal concert. Because all the performers for *Duel Revisited* were also occupied with organising the event, the time allocated for rehearsing with the system was very limited. Furthermore, due to the complexity of the networked setup (see below), much of this time was used to troubleshoot technical hurdles, leaving familiarisation with the musical strategies and their algorithmic implementation up to each performer's individual initiative.

This performance saw the Score module running in location A (Yokohama, JP) and orchestra Y and live coder Y in location C (the concert venue). Orchestra X was also running from location C, but it was remotely controlled by live coder X, who was in a third location (B, Tokyo, JP). Because of the complexity of the network topology, and "to overcome the problem of connecting multiple users behind different NAT routers using a NAT traversal server with the usual 'NAT hole punching' scheme" (Bencina, 2013), the OSC communication was realised using OSCgroups[9] on a public server provided by the MTG group of the Universitat Pompeu Fabra[10] and VPN connection via the Wireguard protocol.[11] The technical requirements for addressing the networking challenges were implemented by the second author by adapting his own *SuperCollider* library.[12] Each orchestra's

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[6] https://ionio.gr/en/news/26444/.

[7] https://meta-xenakis.org/.

[8] https://blog.toplap.org/.

[9] https://github.com/RossBencina/oscgroups.

[10] https://www.upf.edu/en/.

[11] https://www.wireguard.com/.

[12] https://iani.github.io/sc-hacks/.

terminal was connected to one loudspeaker in the concert venue. A diagram of the network is shown in Figure 2. At the time of writing, video recordings are available online for the entire performance[13] and for a short extract video reel.[14]

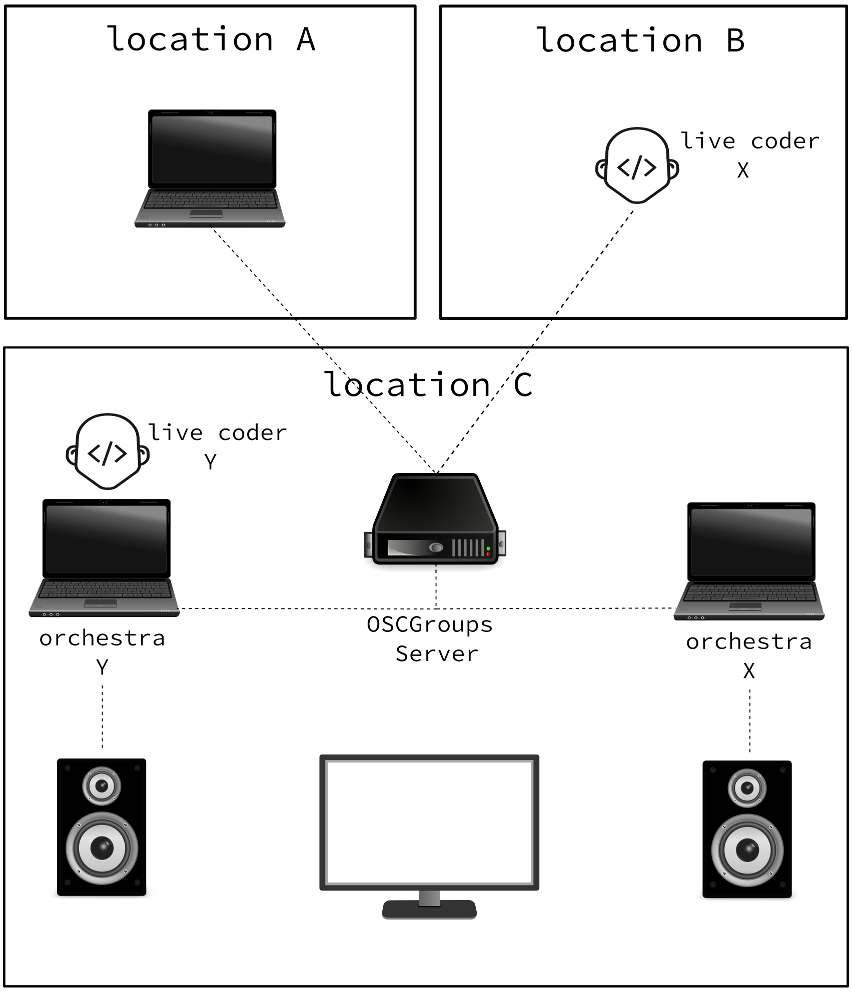

Figure 2: Network topology for the premiere of *Duel Revisited*.
Alt text: Diagram depicting the three locations of the remote networked performance, with each element represented by a literal icon. For example, an icon of a laptop for each terminal, an icon of a stylised human head for each live coder, an icon of a loudspeaker for each sound source, and so forth. Connections between elements are drawn as dotted lines.

4.1 Discussion

Regarding the music created during the performance, it must be noted that the system designer's hope was that the live coders would make time to deconstruct the template scripts provided for the different musical tactics, offering their own interpretation and aesthetic colouring of the sonic strategies described by Xenakis. In reality, and largely due to the lack of rehearsal outlined above, the two live coders strayed little from the templates. As a result, some of the performance might have sounded repetitive at times. While much of the entertainment value of a telematic performance resides in the aesthetic dimension of a displaced physicality (i.e., remoteness) and technological affordances/constraints (e.g., a screen projecting the computer terminal's messages from the Score module, the live coders bent over their laptops typing away, etc.), more careful planning with respect to textural variety is certainly needed in future editions.

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[13] https://www.youtube.com/watch?v=e4LFbfsqPv0.

[14] https://archive.org/details/20221217-kalonaris-diapoulis-zannos-duel-revisited-at-xnpm-22.

A semi-structured interview in the form of open discussion had been planned to provide a qualitative assessment of the performance described. However, the individual commitments of the performers prevented their establishing a mutually convenient time across two continents. Therefore, to gather insight into the experience of performing with the system, an online survey was created and the two participating live coders were asked to complete it. The survey comprised questions on four main aspects of the performance.

First, the live coders were asked about the impact of the system on their average/normal performance practice. Live coder *Y* did not offer particular comments on this while live coder *X* reported the following:

> The game piece involved different coding practices than the ones that I have adopted during my recent work with networked live coding performances. . . . It was easier to learn to use the templates provided by the main author of the piece than to redo the code in my library. More importantly though, the piece required a different workspace configuration than the one I use. Namely, the piece requires separate workspaces for each of the two players, and a shared workspace for the workstation that renders the piece at the concert venue. I coded some extensions to my library to enable execution of code both separately and jointly depending on the local configuration of each workstation (player/coder versus venue).

Both performers found the system's framework somewhat interesting:

> The specific setting of following the rules was an interesting experimentation, particularly in the dyadic setting. (live coder *Y*)

> On the whole, the issue of private versus shared workspaces in a live coding environment was an interesting outcome of the game piece. (live coder *X*)

Second, the performers were asked whether they found the templates provided for the musical strategies adequate in providing sufficient material for kick-starting their own processes and variations on Xenakis's instructions. There was positive agreement on this front, with live coder *X* commenting that

> the templates provided working starting points that I could easily adapt to for my own use, within stylistic limits. The templates had a narrow and limited approach, but this was welcome in the context of the time limits of the project. I consider the imposition of stylistic limitations linked to the practicalities of understanding, adapting and using code a fundamental design concern in the creation of live coding pieces.

The extent to which the templates were appropriated varied between the two players/orchestras, with live coder *Y* reporting changing only some of the parameters in the Synths provided (due to insufficient time for preparation prior to the performance), while live coder *X* re-coded and re-evaluated sections of the Synths (but also lamented a lack of time spent on preparing their own templates).

Third, and on the interaction affordances, the performers were asked whether having a game framework/context for the system altered or influenced their normal interaction with another live coder. They concurred that this was the case and offered further clarification as to why and how:

> It can happen that you just start a collective performance, having no plan, which would more likely result in a messy improvisation where we start playing and jamming without a specific plan, or set of instructions. The specific setting of having predetermined rules made me aware of my part and my co-performer's part, making some tasks slightly easier, like identifying my own sounds and my co-performer's sounds. (live coder *Y*)

> Previous interactions were much more chaotic, because there was not enough time to get to know each others' coding practices and their impact on the piece overall. Familiarising . . . with different coding practices is a major challenge that requires much more time than most ensembles have at their disposal. (live coder *X*)

Fourth, on the aesthetic value, when asked if they thought at any point in the performance that the strategies dictated by the virtual conductor were not musically optimal, they argued to the contrary, albeit not necessarily for the same reasons.

> I have a hard time understanding what would be a musically optimal strategy. At times, it felt more like a chance game rather than having a specific direction. (live coder *Y*)
>
> The strategies reflected the spirit of Xenakis's score and his aesthetic objectives as described in *Formalized music*. There was not much opportunity or motivation to deviate from these strategies. (live coder *X*)

Thus, one performer found the decision-making process opaque and inscrutable, while the other's motivation was instead more rooted in a deeper acquaintance with Xenakis's piece. Subsequently, they were both asked to comment more specifically on the aesthetic implications of schemes that combine predetermined rules of musical conduct (e.g., a given strategy) with bounded freedom of expression (e.g., within a given strategy). Both seemed to agree that having a normative context is not deleterious to the musical outcome of a performance.

> It is undoubtedly more valuable to have imagery of how you would like to evolve a performance and cope during it rather than observing as a third party, where you end up trying to get out of it. (live coder *Y*)
>
> Rules are the cornerstone of all performances, because they create the framework enabling performers to interact and guide their interaction. Making the rules explicit through a game strategy framework is thus a strong tool for understanding the mechanisms of performance and their relationship to the forms created. (live coder *X*)

The responses to the questions on aesthetic value provided some insight regarding the intrinsic conflict in games of musical strategy highlighted in Section 2.2, whereby conductors and performers may be caught between following and subverting the game rules (i.e., adhering to mathematical imperatives or to musical preferences instead).

Finally, a free space was included for the performers to provide any additional feedback they deemed necessary. One performer reiterated the lack of time to get accustomed to the system and the lack of transparency regarding how strategies were chosen in real time.

> Due to the limited preparations, certain things did not work out well for this debut performance. While practising and performing with the system, I felt that there was little time for each instruction, which felt like doing random transitions between the compositional patterns. (live coder *Y*)

For the other performer, experiencing the piece through the system provided further insight into Xenakis's work.

> The experience departed from my customary, self-developed networked live-coding practice, because it relied on the main author's interpretation of Xenakis's theory and work. Furthermore, the presentation framework and other constraints were different to what I was accustomed to. On the whole, though, it was a very enriching and instructive experience and I appreciate the opportunity to study Xenakis's thought from a different point of view through this collaborative experience. (live coder *X*)

5 Reflection

Some important themes emerged when probing the scope defined by this new version of Xenakis's *Duel*. While it is up to the live coders to investigate the inner workings and the theoretical background of this piece, perhaps rendering these more explicitly in the context of rehearsals might help develop a sense of ownership when performing with the system. This could be done simply by including more commented sections in the live coders' boilerplate scripts, where basic notions of game theory and/or how the conductor might choose strategies are explained briefly. As outlined in Section 3, the decision-making framework and the sequence of strategies follow more a process of optimisation than pure chance.

Despite this, the process might be perceived as arbitrary: would the juxtaposition of musical strategies feel less "random" had the conductor(s) been human? In the case of breaking a tie between equivalent reward strategies, for example, one would not know if a given strategy was chosen due to rushing, aesthetic preference, a failure to consider the alternatives, or simply impulsive behaviour, among other reasons. When machines are involved in the creative process, however, there is an added onus upon the system's designer in that (some of) the internal mechanisms must be exposed to the human users. While in the case of *Duel Revisited* the decision-making agents are rudimentary and the rules are simple, helping performers understand what goes on in the Score module might help in reducing the negative bias toward machine-generated output (Grassini & Koivisto, 2024; Ragot et al., 2020; Tubadji et al., 2021).

Notwithstanding the limitations of the system described in this article, the use of computational models for the conductors in charge of the musical strategies did offer opportunities to re-examine this seminal work by Xenakis, the relation between rational and intuitive decision-making processes, and the aesthetic implications of norm-based/formalised musical interactions. In the particular instance of *Duel Revisited* described in this article, this affordance extends to one's own creative practice in the context of live coding and networked performance, as the commentary offered by the performers shows.

As for future work on this project, the authors can envisage explorations towards fully automated implementations of the piece. For example, the orchestras could be delegated to agentic modules (e.g., generative music models) using Xenakis's definitions for each musical strategy (see Section 2) in any given *stage game* (i.e., a repetition of a base game in iterated games) as the input prompt. Further extensions in this direction could see the conductor module modified by the reintroduction of Reinforcement Learning (RL) agents, as originally undertaken by Kalonaris (2022) when demonstrating the importance of straying from purely rational decision-making for the sake of musical variety and contrast. For the same reasons outlined there, the RL paradigm would have to be complemented by some arbitrary injection of randomness/surprise to counteract the inevitable convergence towards the Nash equilibrium.

Steps in this fully automated direction would have to be taken in the awareness that, in this challenging age of increasing blending between biological and artificial intelligence, it has become a cliché to embrace technology as a tool to help us discover what it means to be human. Under this stance, no technology is inherently bad or good – these are, rather, value judgements reserved for its uses. This remains a complex and controversial topic, and it would be interesting to engage with this conversation when the contribution of a more autonomous version of *Duel Revisited* warrants it.

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Appendix

A **game** is defined as follows:

- A finite set of **players** N
- for each player $i \in N$ a non-empty set A_i representing the set of **actions** available to player i.
- For each player $i \in N$ a **preference relation** $\succsim_i$ on $A = \times_{j \in N} A_j$ (the set of outcomes by A).

A **utility function** maps rewards (or **payoffs**), to actions $u_i : A \rightarrow \mathbb{R}$, so that $u_i(a) \geq u_i(b)$ whenever $a \succsim_i b$. Games can be distinguished between **constant-sum** and **variable-sum** games. In constant-sum games, the payoffs for each possible combination of actions sum to the same constant C. A particular case of constant-sum games are **zero-sum games**, whereby one player's gains are the other's losses (payoffs sum up to 0). In variable-sum games, rewards are neither symmetrical (opposites) nor sum up to a constant.

A **strategy** is a decision algorithm which considers the options available under a given scenario: a complete contingent plan that defines the action a player will take in all states of the game. A **strategy profile** is a set of strategies for all players which fully specifies all actions in a game.

Games can be *simultaneous* or *sequential*, which are normally represented differently: **normal form** (or **strategic form**), expressed as a payoff matrix, and **extensive form** (or **game tree**), represented as a graph. To formally define extensive games, one also needs:

- A set H of sequences where each member is a **history** and each component of a history is an action. A history $(a^k)_{k=1,\ldots,K} \in H$ is **terminal** if it is infinite or if there is no a^{K+1} such that $(a^k)_{k=1,\ldots,K+1} \in H$. The set of terminal histories is indicated as Z.
- A **player function** P that assigns to each non-terminal history (each member of $H \setminus Z$) a member of N.

Games can be further categorised using **perfect** versus **imperfect** and **complete** versus **incomplete** information. The former describes whether or not players have knowledge of each others' actions and history. The latter is instead concerned with having or not having common knowledge of each player's utility functions, payoffs, strategies and "types".

Simultaneous games can be converted from normal to extensive form, and vice versa (**induced normal form**). Figure 3 illustrates this procedure for a popular zero-sum game known as *Matching Pennies*. An **information set**, indicated as a dotted ellipse enveloping decision leaf nodes, is used to indicate that player y, while moving after player x, has no knowledge of what action the opponent chose and, therefore, whether she finds herself under the right or left leaf node.

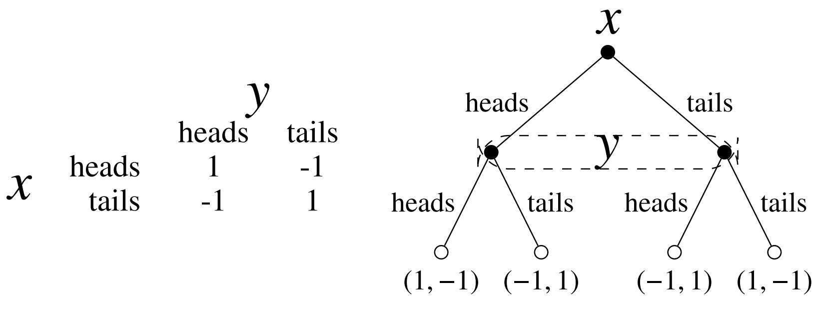

Figure 3: A popular zero-sum game known as *Matching Pennies*, shown in matrix form (left), and in an equivalent extensive form (right).

Solutions are optimal combinations of strategies which ensure the best outcome for a given or for all players. For strategic games, different game-theoretic solution concepts include **maximax** (maximise one's payoff), **maximin** (maximise one's minimum payoff, also known as choosing the best of the worst possible outcomes), and **minimax** (minimise one's maximum loss). In a two-player zero-sum game, when the matrix has a **saddle point**, meaning a given action pair yields the best outcome for both players (i.e., neither could do any better), the maximin and the minimax strategies produce the same result. The **Nash equilibrium** for a strategic game $\langle N, (A_i), (\succsim_i)\rangle$ as the solution where no player has an incentive to change strategy given that no one else does, and express it formally as a profile $a^* \in A$ for every player $i \in N$ so that $(a^*_{-i}, a^*_i) \succsim_i (a^*_{-i}, a_i)$ for all $a_i \in A_i$. If there is no saddle point, one can use **mixed strategies** (Morgenstern & von Neumann, 1947). This involves randomising one's action selection with weighted probabilities that ensure statistically optimal outcomes. In other words, each player makes the other indifferent between choosing one action or another, so neither player has an incentive to try another strategy.

For an extensive game $\langle N, H, P, (\succsim_i)\rangle$, and having defined $O(s)$ as the outcome of a strategy profile $s = (s_i)_{i \in N}$, the Nash equilibrium will be the strategy profile s^* for every player $i \in N$ such that $O(s^*_{-i}, s^*_i) \succsim_i O(s^*_{-i}, s_i)$ for every strategy s_i of player i. Mixed strategies can work analogously to what is seen in strategic games, whereby a Nash equilibrium in mixed strategies for extensive games can be expressed as a profile σ^* of mixed strategies so that $O(\sigma^*_{-i}, \sigma^*_i) \succsim_i O(\sigma^*_{-i}, \sigma_i)$ for every mixed strategy σ_i of player i.

The notion of **subgame perfect equilibrium** is a refinement of the Nash equilibrium defined above that accounts for history-dependent best responses so that, for every non-terminal history $h \in H \setminus Z$ for which the player function is $P(h) = i$, $O(s^*_{-i}|_h, s^*_i|_h) \succsim_i O(s^*_{-i}|_h, s_i|_h)$ for every strategy s_i of player i, for the subgame $G(h)$. Subgame perfect equilibrium is obtained using **backwards induction**: starting from the terminal history, one finds the best response strategy profiles or the Nash equilibria in the subgame, assigns these strategy profiles and the associated payoffs to be subgames, and moves successively towards the beginning of the game.