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ORIGINAL ARTICLE

Aesthetic and technical strategies for networked music performance

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Abstract
Networked music is no longer a future genre: the global quarantine event of 2020 launched the concept of performing together over the Internet into the mainstream. While the demand for performing at a distance may be a new imperative, musicians find themselves faced with technological and performative processes that do not appear to be suitable for performing music together online, due particularly to network latency which disrupts the ability for musicians to synchronize. The research presented in this paper investigates and challenges the reasons why networked music is not readily embraced by musicians and describes how that might change, by way of interviews with practitioners and an in-depth review of the technical constraints. Limitations that might cause frustration are in fact shown to have creative strategies that give rise to aesthetic approaches, distinct to the platform. By exploiting the constraints, in tandem with developing technology designed specifically for remote performance, aesthetic implications arise that not only accommodate the inconveniences of latency and acoustic feedback but can help us adapt and transform how we engage in real-time online, towards a future where we can imagine performing together over even more dramatic distances such as high-latency, low-bandwidth locations outside of urban areas—or even over galactic distances.

Keywords Networked music performance · Online performance · Contemporary music composition · Music technology · Network latency

1 Introduction

In March 2020, one week before the world went into quarantine for COVID-19, I had given a week-long workshop on the topic of Networked Music Performance at the Royal Conservatory of the Hague. A week later the students realised that their May concerts would not be taking place in the concert halls, and immediately embraced network technology to adapt and create new work. I was and remain deeply inspired and hopeful for a future of distributed music making. My approach to performing over the Internet is informed both by the research I have gathered during my fifteen years as a provider of remote recording services for the audio production and post-production industry, and by my work as a composer/performer. The days and weeks following the global quarantine were a profoundly significant time both professionally and musically as myself, and my colleagues were overwhelmed with requests from around the world for services for musicians and audio professionals to work remotely, an especially difficult task for musicians and music makers who have traditionally relied on the ability to collaborate together in the same physical space. The concern surfaced constantly: how can musicians work together online, when the very nature of the Internet disrupts musical performance due to latency? The question of how we can perform using a technology that is disruptive to performance was asked so often that a new forum[1] was created dedicated to the topic to save us from typing and re-typing similar replies. In summary, Internet latency will never go away as it is a property of physics—it is constrained by the speed of light; further, working remotely from each other creates additional technical demands on musicians, such as acoustic feedback which is an unavoidable property of digitization, transmission and reproduction. In order for networked music performance to become a normal part of our music-making process and for musicians and audiences to embrace working together over distances as a rewarding pursuit in itself, rather

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[1] A forum for musicians to share information on the topic of Networked Music Performance and technology was created at https://forum.latencynative.com.

than some anomaly we must endure, we must consider the constraints and affordances of network technology, such as latency, digital compression and digital reproduction, and design and implement tools and performance processes that exploit these constraints; then, performing over the Internet will begin to feel natural to us.

Not so long ago, I would look forward to regular video chat sessions with my young nephews as they ate breakfast at the kitchen table in their family home in New Zealand while I ate my evening meal on the other side of the world. They quickly took to the game of taking me along for playtime and, in this manner, I saw their world through the view of a camera lens. I accompanied them alongside games of playing pirates, chasing the chickens, and hiding me under a pile of blankets. In that extraordinary way of children, there was no shortage of possibilities for play as long as our digital, oft-stuttering streams of audio and video maintained a sufficient representation of ourselves. Through these interactions, I came to fully understand that mediating remote presence requires the management of expectations, which can be creatively applied and interpreted. As experienced by my nephews, I *was there* and when I have the fortune to visit them in real life, we play no differently except in genre, be it a foot chase around the house instead of a game of digital hide and seek.

This sense of togetherness that affords remote play is reliant on two key factors: liveness, so we sense we are performing together in time, and reproduction fidelity, so we have sufficient information any moment to inform us about how we are performing together. By examining these two factors on a technical and musical level, composers and musicians can exploit the affordances of Internet-based networked music performance to discover new creative forms of performance that embrace Internet technology and all its constraints as being inherent, unavoidable properties of Networked Music Performance.

The following text was largely written in 2018, which now seems a completely different epoch in human civilization, given how rapidly the Internet streaming and collaboration landscape changed between the first and second quarters of 2020. While I have updated a number of references to reflect recent technical developments, my core argument—that, rather than we should seek to reproduce offline experiences online, the Internet offers unique affordances for entirely new ways of performing together—has strengthened and I am grateful for the opportunity to publish at this critical time as new ideas and aesthetics are emerging.

2 Background and contexts

Networked music performance offers a wealth of potential for new aesthetic approaches. As a method of reproduction, it embodies Gibson's (1986) concept of an affordance machine in the way that it informs us about the environment in which the music is created: when we transmit our performance over the Internet we must first digitise it; thus, we have access not just to the performance but to its data; we can, simultaneously, analyse from both human and computational perspectives. Furthermore, as an artificial, easily manipulated method of reproduction, it adds a powerful extension to Reybrouck's (2014) idea of music's ability "to bring together productive and experiential aspects of musical affordances … that prompts the listener to experience the sounds as if they are involved in their production" (p. 17). If the listener can imagine how they are physically reproducing the sounds made by the pianist, they can equally imagine that they are inhabiting the remote space of the pianist, which is 'not here' and is perhaps on the other side of the world.

Music technology evolves rapidly and as it does so it has an undeniable influence on the creation of new musical forms. Throughout history, musical development has been tightly linked with advances in technology. Entire new forms of music have emerged thanks to technical inventions, such as the 1780s arrival of the pianoforte, which "urged composers towards more intense kinds of expression" (Swafford2014, p. 59).[2] New mechanical instruments that extend performance ability, simulation, and realisation make clear the definition between human and machine agency, arriving at the modern day where instruments create what Nicolas Collins (2002) terms 'impossible music', music that could not be created without technical means.

In the last two decades with the Internet's extended reach of global broadband access and the development of digitization and transmission technologies, many methods of networked musical collaboration have been explored. Regardless, for all the technical developments of the recent decades, no mainstream movement exists for the performance of real-time music over the Internet[3]. Musicians largely use

[2] "New kinds of figuration, written articulations, pedal effects, and dramatic contrasts of volume began to appear in keyboard music, which in turn urged composers towards more intense kinds of expression" (Swafford, 2014, p. 59). Beethoven's playing was the "result of years of not only practising the pianoforte but also thinking about how it should be played, as distinct from the harpsichord or clavichord" (Swafford 2014, p. 121). Further, Beethoven insisted that pianoforte manufacturer Stein extended the keyboard length, thereby forcing others to buy new instruments to play his new work.

[3] Since March 2020 musicians are seeking solutions on a global scale however this is largely to reproduce the offline experience. They hope to return, as quickly as possible, to the traditional concert venues.

the Internet primarily as a file-transfer service for offline collaboration or at best, perform to pre-recorded or predetermined events.[4]

While new digital technologies have a deep impact on production and distribution (Poole 2011) and a considerable number of networked music performances have been staged, "after a few years of experiments through the Internet, the interest has shifted toward the use of [networked music performance] for composition only and advancement in avant-garde music practice" (Gabrielli and Squartini 2016, p. 1).[5] Compromises made by the designers of the Internet have had long-lasting effects on real-time media transmission: data are packetised, and each packet may arrive late and out of order, which causes latency—the time it takes for data to be transmitted—and 'network jitter'. Networked audio can mitigate errors by implementing transmission protocols and codecs that compress and retransmit data, yet ultimately, latency and jitter are unavoidable over the public Internet. The result is 'best effort', where uncertainty must be designed for.

Latency affects time-keeping and human-level rhythms, core properties in the act of making music together. Lazarro and Wawryzynek (2001) declare that "the total latency must be kept reasonably short for the networked music performance system to be usable" (p. 157). I disagree and argue that latency will become a fully exploited and accepted property of networked music as it affords distinct creative opportunities. While the technical limitations of the Internet may disrupt traditional musical performance, the potential for making music together over the Internet remains to be fully realised; i.e. new aesthetic forms and genres remain to be seeded, "opening up a wide field for invention, intervention, and surprise" (Rohrhuber 2007, p. 154) where networked music performance offers "a means of reflection for the artists and the composer over new media technologies" (Gabrielli and Squartini 2016, p. 3). I suggest that networked music performance tends towards an aesthetic where "the resulting sound is born of the use of instruments in ways unintended by their designers" (Cascone 2000, p. 396) and that basing a practice on the fragility of the networked experience leads to "situations resulting from the on- and off-line network interconnection experience" (Beiguelman 2006) where the digitised signal provides co-ordination of "multiple and simultaneous readings of contents mediated by countless uncontrolled variables" (Beiguelman 2006). The potential for new forms and genres suggests exciting opportunities for research, particularly in generating and transmitting 'vital information' by musical and technological means. Nevejan (2007) suggests that "when in trouble, one needs good information and good communication; i.e. one needs 'vital information'" (p. 175), which is information that "supports survival for a specific person in a specific place at a specific time" (Nevejan 2007, p. 175). Vital information in networked music is crucial in facilitating synchronisation, in contrast to the traditional performance setting, where ensemble musicians rely on low-latency audio and visual communication.

3 Primary characteristics of the medium

The primary characteristics of networked music performed over the public Internet are defined by technology and the imposition of that technology on participants. Network latency cannot be removed—transmission speed is ultimately limited to the speed of light due to the natural laws of physics. Even if we are to obtain low-latency transmission technology[6], data are subject to additional latency at any point it switches from one device or network to another. Further, unless the performers are able to work over dedicated high-grade institutional connections such as Internet2[7], latency cannot be reliably predetermined or fixed at a certain value, even during the duration of a performance, because data are packetised and then transmitted over the network on what may be different paths for each packet, possibly arriving late or out of sequence. Therefore, latency and uncertainty are primary characteristics. Secondly, networked music performance requires at least two participants: a transmitter and a receiver, who are multi-located and multi-authorial and each inhabiting their own distinct acoustic space. The third core characteristic of networked music is the digital mediation of presence: i.e. networked music is performed over a digital network where the signal is processed and transmitted. Performative relationships are managed by means of this transmission. In practice, the characteristics of latency and uncertainty can be applied to

[4] Observing my own daily interaction with sound professionals, real-time audio is mostly used for monitoring when working with music; e.g. a composer will listen to an orchestra or musician perform alongside a guide track or score to provide feedback as the performance occurs. Recorded files are then transferred after the listening session back to the composer for local mixing and editing.

[5] For a comprehensive overview of the history of music technologies and performance over the Internet, see *Wireless networked music performance*, chapter 2.2, A Brief Timeline, pp. 6–19.

[6] While in principle we can "transfer data at nearly the speed of light" (Singla et al. 2015) in fact Internet latency is a magnitude slower than the speed of light, particularly on consumer networks, due to infrastructure constraints and costs.

[7] Internet2 is an institutional network that can "support phenomenal numbers of channels at long distance and low latency. As these linkages become more commonplace (and extend into communities outside universities) they will create an 'always on' real-time media web that includes a different kind of acoustical medium" (Chafe 2009, p. 28).

networked music transmitted via analogue means, such as radio broadcasts or copper phone lines; however, listeners are less frequently listening to analogue radio transmissions as they migrate to the Internet, satellite radio, and podcasts. In addition, digital fibre optic and wireless installations have all but replaced analogue telephone infrastructure.[8] Given the increasing level of digital communication technologies, transmitted data should be assumed to be subject to compression and the network effects of packetisation, which are the core digital mediation parameters.

Secondary properties are defined as musical relationships such as rhythm, harmony and timbre. In networked music performance, these properties are directly affected by how the composer negotiates the primary characteristics: e.g. latency affects the ability of musicians to be temporally responsive to each other, and a multi-located performance removes eye contact as a visual aide for synchronisation. These constraints thereby necessitate new strategies in musical synchronisation.

Tertiary properties are the parameters and consequences of how certain rules are applied to those parameters; i.e. the ways in which the composer personalises their music according to the way they realise a constraint's rules. This includes practices such as manipulating the variable amount of latency between network participants, or sending unexpected data to the codec for the purposes of exploiting timbral potential.

Lazzaro and Wawrzynek (2001) defined networked music performance as the "practice of conducting real-time music interaction over a computer network" (p. 4). I add to this definition of networked music performance in line with my own personal interpretation, which I derived by way of, and subject to, the three primary characteristics extrapolated above in relation to the following three conditions:

(1) I refer to the network exclusively as the public Internet, which is prone to latency and uncertainty.
(2) I apply the concepts of multi-located and multi-authorial, which refer to music made between multiple spaces and multiple human participants, respectively.
(3) The means of communication between participants is encoded and transmitted by digital network technology; therefore, communication is digitally mediated.

Within the boundaries of these characteristics, I consider the limitations and affordances of how we perform music over a network. When we communicate with each other via technology, we are experiencing mediated presence: i.e. a networked performance mediates human presence by exchanging 'vital information' via technology. Mediated presence is partial, it lacks the full-sensory experience of real-life interactions. The information we expect to have during an interaction is limited; therefore, synchronisation becomes difficult and we easily misunderstand each other. When performing music over a network, we need to generate and transmit vital information that facilitates synchronisation.

We further accommodate mediated presence by adapting our expectations and 'orchestrating' or 'performing' presence (Gill 2015) actions that permit the synthesis of new modes of communication and expression, which are often converted to more abstract forms that are transmitted easily. The way in which the composer manipulates the presence by making technical or musical choices in turn affects the relationship between participants: i.e. the performative relationship is the dance between a constraint and acting on that constraint.

My understanding of performative relationships via mediated presence is heavily influenced by Nevejan's (2007) YUTPA (i.e. being with You in Unity of Time, Place, and Action) framework. Nevejan describes how the "four dimensions of time, place, action and relation have different values between You and not-You, Now and not-Now, Here and not-Here, Do and not-Do" (Gill 2015, p. 148). These dimensions are useful for understanding the constraints, artificial or otherwise, which are created when presence is mediated by technology. Nevejan's (2007) research shows that such relationships can be measured and categorised, and through this process, we can create vital information and expose new aesthetic strategies by the exploitation of the fabrications, synthesises and synchronisations of presence as influenced by digital mediation.

3.1 Strategies and approaches

To encourage remote participation, it must be shown that networked music performance is an invigorating and satisfying musical pursuit with achievable aesthetic challenges and a rich circumstance of affordances for future work. Networked music performance involves three primary categories: latency and uncertainty, digital mediation and multi-location. In a reading of Moles (1984); Rohrhuber (2007) describes artistic expression as a "message transmitted by an artist (the transmitter) to another individual (the receiver) over the systems of perception (the channel)" (p. 145). These categories of message, transmission and reception work together to comprise the vital information that continuously forms the musical experience as encapsulated by the sound image in which musical participants interact. The ability to manipulate the sound image by generating and modifying

[8] The New Zealand Telecommunications (New Regulatory Framework) Amendment Bill of 2017 aims to allow telecommunications companies to actively discontinue support for analogue copper phone services by removing service regulations.

both the message (as sound) and the way the messages are transmitted reassures us that (a) we can be participatory with the remote sources and (b) we can imagine and apply strategies towards an aesthetic of networked music performance.

3.1.1 Aesthetic creation contexts

The French curator Nicholas Bourriaud (2002) defined the term 'aesthetic' as "a set of artistic practices which take as their theoretical and practical point of departure the whole of human relations and their social context, rather than an independent and private space", where artists facilitate rather than make and consider art as information to be exchanged between the artist and viewer. Through reading Polanyi, via Gill (2015), I understand aesthetics as an act of knowing involving 'tacit knowledge', which is the "way we are aware of our neuronal processes in terms of perceived objects. This has a mediatory structure, hence we know more than we can say" (p. 21). From this position, I apply the term 'aesthetics' to denote both a way of knowing and a way of doing.

An aesthetic is created by poiesis[9] through the combination of decisions made according to the real-time experience of what is happening now in play with tacit knowledge: i.e. "poiesis, as it pertains to the distance collaboration" means "creating with intentionality" (Pignato and Begany 2015, p. 119). Aesthetics exposes musical relationships, which to date are largely built on the assumption of musicians who share the same space. The introduction of latency and multi-located digitally mediated presence requires a departure from the traditional musical strategies of vertical harmony and synchronous rhythmic relationships towards aesthetic strategies of liveness and uncertainty.

The concept of liveness is used to distinguish between music that is in the act of creation and has not previously existed in its complete form, as opposed to music that has already been created. Through liveness, we experience participation and interactivity, which engenders resonance between stimulus and action, thereby strengthening social connections. I appeal to Auslander's (2012) premise of liveness being a "historically variable effect of mediatisation" where "prior to the advent of these technologies (e.g. sound recording and motion pictures), there was no need for a category of 'live' performance" (p. 3), and I continue this idea to suggest that the arrival of networked music requires approaching liveness from new angles. Liveness is disrupted by the act transmission, which unsettles the naturally developed tendency for musicians to sound together; therefore, vertical harmony and synchronous rhythms are laborious. For most musicians, this is a most profoundly disorienting experience and causes many to state that you cannot play music together over the Internet.[10] Flipping this assumption by saying you can play new kinds of music together over the Internet opens up opportunities for listening and experiencing music in new ways.

3.1.2 Four aesthetic approaches

An aesthetic strategy of networked music performance is a complete, categorisable expression of the application of music given the primary characteristics and constraints; i.e. a set of principles underlying the stylistic choices made during the creative process. I refer to Curtis Roads' excellent *Aesthetic Foundations* for a relevant discussion on aesthetics as it applies to computer music. Roads (2015) further defines aesthetics as an "inspired choice" or a "particularly satisfactory choice given the context" (p. 15). My take on this is that the more informed a composer is about the tools—available now and the one we can imagine we will have in the future, the more choices for inspiration.

3.1.2.1 Approach 1: post-vertical harmony Harmony is a vertical property, where multiple voices sound together at the same time to create an experience of simultaneous complexity. Counterpoint and melody are horizontal properties that create complexity over the temporal, horizontal plane. I introduce the term 'post-vertical harmony' because the experience of harmony, counterpoint and melody as known in traditional music is disrupted when time keeping is unstable. Post-vertical harmony means embracing a time-shifted skewed listening experience; i.e. the experience of knowing that the harmony you are hearing is the result of network latency (Fig. 1).

To the listener, a completely different harmonic experience happens with each permutation as shown in Figs 2, 3, and 4. Such an effect of harmony shifting over time is familiar through works such as Ligeti's 'micropolyphonic' webs based on constant transformation (Roig-Francolí 1995) and the mensural canon effect of an unfolding melody that expands underneath itself creating harmonic density, a modern example being the opening movement in Shostakovich's fifteenth symphony.[11] There are fundamental harmonic processes that are compatible with a networked aesthetic: e.g. detached layers of sound, macro-structured to allow for

[9] Nattiez (1990) defines poiesis as "the *link* between the composers' intentions, her mental schemas, and the result of this collection of strategies: that is, the components that go into the work's material embodiment".

[10] From private conversations with many musicians over the years during my time working with networked audio in a professional context as a service provider with my company Source Elements (https://source-elements.com).

[11] From rehearsal number 27, *Symphony No. 15* in A major (Opus 141), Dmitri Shostakovich.

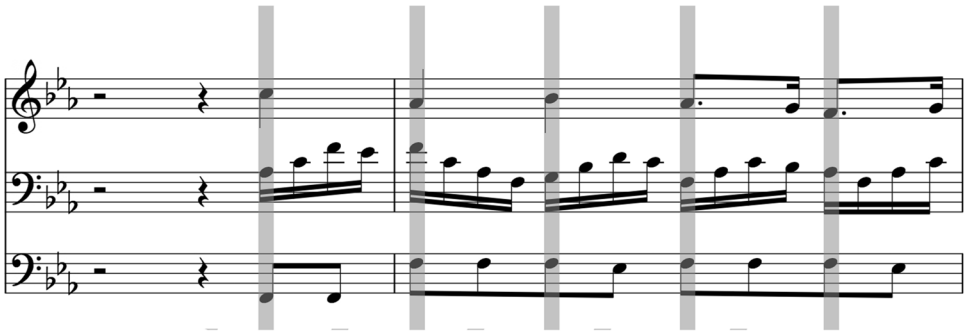

Fig. 1 Opening bars of Bach's Choral BWV639

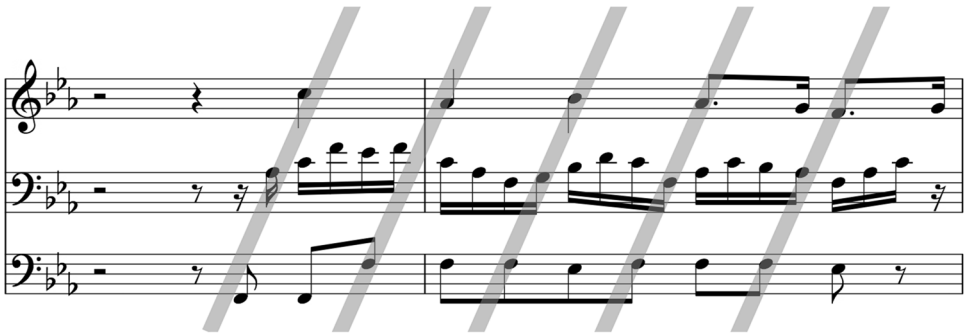

Fig. 2 Each line is 375 ms ahead of sync of the previous line (typical latency over intercontinental network and equipment)

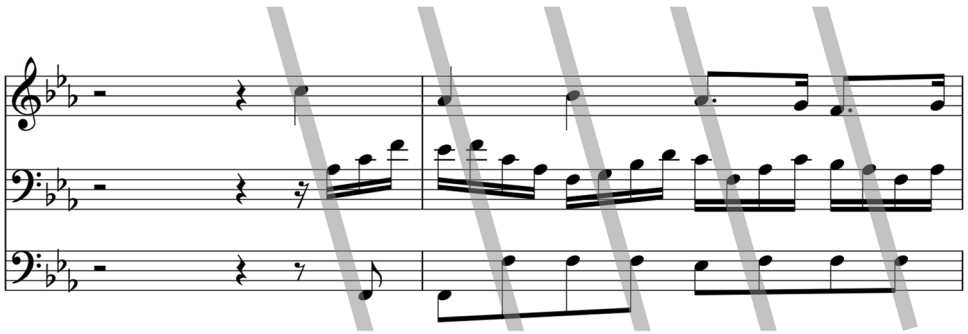

Fig. 3 Each line is 375 ms out of sync after the previous line

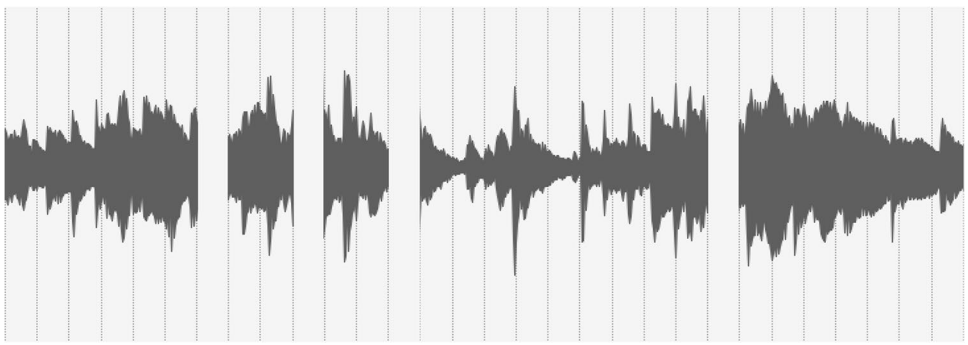

Fig. 4 Visual representation of 10% packet loss in a waveform

unstable internal motion. Where "polyphony is what is written", says Ligeti, "harmony is what is heard".[12] I have no doubt that these composers would feel completely at home given the latency constraints of the network. Nebulous compositions such as Ligeti's 1967 *Lontano* and Xenaki's 1953 *Metastasis* embody processes that would translate directly to multi-located performance because these works depend on conceptualising time instead of a melodic theme.

3.1.2.2 Approach 2: resonance and multi-located timbral fusion Networked music performance mirrors the electroacoustic experience of Schaeffer's (1977) reduced listening, "which strives to strip sound of distractive visual presences" (McKinnon 2007, p. 1). Networked music presents an additional detachment in the listening experience: without being present at the moment of sound-making, sounds created by remote musicians fuse together to be experienced as singular timbres—new instruments—as "we forget about what agent, object, or action made the sound or what the sound signifies; we focus only on the musical properties of the sound—its internal rhythms, its timbres and textures" (Andean 2013).

In networked music, latency affects both the rate of succession and therefore the timbre of the source sound: e.g. two flutes sounding the same note in 'composite space'[13] are now different because the attacks and envelopes are even more asynchronous than occurs naturally with non-machine performances. Latency can be exploited to further detach musical harmonies and rhythms: i.e. asynchronous timbres, loudness, and pitches have the potential to create a fusion of succession of sounds when overlapped in quick repetition, much in the way that film when played back at twenty-four frames a second is perceived as a seamless image (Seashore 1936). Music psychologist Carl Seashore's studies on vibrato were instrumental in my considering the timbral implications of networked music performance and the ability to create entirely new sounding instruments that echo and shimmer between the networked locations, where distinct sources are perceived as forming fused timbres. Seashore (1936) claimed that timbral deviations, such as vibrato, create an auditory illusion which result in our hearing something entirely different than that which is performed. This illusion is the sound world that happens in the act of creation.

3.1.2.3 Approach 3: vital information and performative relationships While the Internet has been transformative in many fields, including the arts, music collaboration, and creation over the Internet remained largely non-real time, even given that global forces in 2020 encouraged musicians the world over to investigate networked music opportunities. The lack of online collaborative concerts suggests that distinct issues must be resolved before musicians as a whole embrace networked music performance as part of their repertoire. The presence that is mediated over the network disturbs human-level rhythms (Gill 2015) by interrupting life-long musical practices of playing music together and rhythmic synchronicity, which interferes with honed musical abilities for virtuosic performance based on traditional ensemble dynamics. Networked music performance clearly creates extra-musical demands on the participants as they attempt to achieve temporal stability through their performance. Critical information must be created and exchanged in ways other than the traditional cues used by musicians in composite space. Nevejan (2007) states that "for information to be vital, it has to touch upon our natural presence physically or socially. Mediated presence, which generates vital information, will also ultimately have this effect" (p. 174).

I propose that the vital information that facilitates performative relationships over a network can be created and transmitted as musical information. The understanding of how vital information is used in a networked music context is of high value: e.g. we can make use of notational music events in the score and implement technical solutions that reproduce and communicate clock and event messages. By providing this vital information, the composer creates an environment that mitigates synchronisation concerns for musicians, leading to the development of new performance structures.

3.1.2.4 Approach 4: a post-digital approach Inspired by Nicholas Negroponte's 1998 comment, "the digital revolution is over", Cascone (2000) coined the term, 'post-digital', in commenting that the "revolutionary period of the digital information age has surely passed. The tendrils of digital technology have in some way touched everyone" (p. 12). Cascone's (2000) thinking follows Walter Benjamin's thesis that "mechanical reproduction results in fundamental and traumatic derangement of the senses, which anticipated certain aspects of [Marshall] McLuhan's idea that media technologies constitute new extensions of the sensory organs of man—*outerings* of the body" (Taylor and Harris 2007, p. 24). All of this means to say that technology that reproduces reality does not reproduce it in human ways, but it splices it to pieces, duplicates it, reorders it, destroys much of it, encodes and decodes it, transmits it, stores it, deletes it and reproduces it with or without a grainy veil of decompres-

[12] Ligeti, *Lontano* LP program notes, 1984, as cited by Bauer and Kerékfy (2017).

[13] "Composite space" is a borrowed term from Sarah Weaver (2016). It refers to participants being present in the same physical space as opposed to being in multiple, separate spaces and connecting over the Internet.

sion. This should be taken as a cautionary tale: i.e. reality can be reproduced in ways quite different to the original and we should all take care not to believe any of it; or, this can be taken as a great opportunity for messing with reality. As Cascone (2000) notes, "technological failure is often controlled and suppressed" (p. 13) whereas the post-digital approach embraces and illuminates failure. Even when not faced with packet loss, time-stretching, or changes in latency during a performance, the "uncertainty of causation is often an integral part of the aesthetics" (Rohrhuber 2007, p. 148). The resilience and musical creativity of the participants is paramount when facing latency and multi-located considerations.

4 Parameters for exploitation

Being digital, the means of transmission can manipulated on many levels. Being music, what is transmitted is highly expressive. These two premises offer strategies for approaching the aesthetic considerations outlined above in networked music performance. I summarise below the primary characteristics:

- **Latency and uncertainty**: the unavoidable artefact and unstable property of the network transmission.
- **Multi-located, multi-authorial**: the collision of sound images that exist on multiple temporal planes, creating new timbral experiences and questioning perceptions of authorship and ownership.
- **Digital mediation**: the deconstruction and reconstruction of the sound image, permits reproduction in any form.

I consider the musical affordances of the primary characteristics using these four aesthetic approaches:

(1) Post-vertical harmony.
(2) Vital information and performative relationships.
(3) Resonance and new timbres through multi-located fusions.
(4) The post-digital aesthetic.

I argue that everything else that addresses the sound image, be it as perceived by participants, listeners or the concerns regarding DSP[14] or placement of audio speakers[15] has been addressed with sufficient depth in other texts.

4.1 Latency and uncertainty

Latency—the time difference between sending and receiving data over a network—is fundamental to the experience of networked music performance. To gain insight into how composers and performers manage latency, I spoke with Sarah Weaver whose decade-long experience in composing, conducting and performing with music over a network is currently culminating in her PhD on networked music. Sarah's interest in the medium began in 2006 with early collaborators Pauline Oliveros, Chris Chafe, and Mark Dresser. Oliveros (2009), a pioneer of early networked music performance, stated that as "the technology improves exponentially and ubiquitously then eventually there will be no reason not to perform music at a distance" and "making music together makes friends" (p. 2).

Latency is the essential grain of networked music performance that articulates the physical limits of a system and cannot be programmed away. It is a technological implication that cannot be solved by technology alone, as much as we mitigate the limitations of transmission technology with high-fidelity reproduction techniques and telemetric analyses, our interactions are mediated, disrupting our natural way of being together. Sarah (Weaver 2016) explains that something new happens when we traverse distance with technology because humans remain analogue even when we use communication technology that works on a radically different timescale. Latency can be experienced as a site-specific phenomenon; e.g. as reverberant artificial structures or cavernous natural spaces. It can be introduced purposefully with electronic means, such as network latency or analogue delay. It can also be produced through musical intentions such as 'groove' elements, grace notes, rubato, and free tempos. Sarah is familiar with performing networked music over ultra-low-latency systems such as Internet2 and observed that latency's "threshold is key in creating a perception of 'synchrony'" (Weaver 2016), where the lower the latency, the higher the synchrony. Gill (2012) defines the term 'synchrony' as "the period and phase-locking movement patterns or sound to an external referent. In other words, it is the capacity to move in time to the next expected regular beat from outside" (p. 112). Sarah further extends synchrony to suggest that "to connect live and perform together live is a different level of intimacy" and, given a set of musical instructions, remote participants can be musically synchronised. I interpret Sarah's observations as referring to the properties of latency as vital information. The delay and jitter values tell us critical information about the environment that directly affects the way we respond to each other musically.

[14] Digital signal processing (DSP) is the method by which signals, such as sound, that have been encoded into digital form are intentionally manipulated (Thon 2003).

[15] Sound projection or 'diffusion' is the active practice, originating with the French acousmatic tradition, of redirecting sound to loudspeakers (Emmerson 2017).

While certain types of music-making over a network are complex or impractical due to the disruption of rhythmic expectations, other forms of music are well-suited and exquisitely distinct when composed with latency in mind and the audience's perception of latency is related to expectations. When surveying an audience after a networked music performance, Sarah "asked them if they experienced any delay or latency, and they almost unequivocally said, 'what do you mean', like they just didn't know that there was any delay because we had bridged it with the music" (Weaver 2016).

The primary effect of latency is the unavoidable—and possibly unstable—counterpoint caused by both the network and the result of humans attempting to synchronise remotely. I conversed on this topic with Ray Lustig, a New York-based composer whose 2013 work *Latency Canons* approached latency as the focal characteristic for orchestra and four distributed ensembles. An audience member and reviewer noted that for Ray, latency was far from being an obstacle: "where many composers might bemoan a technical difficulty that must be overcome in the service of precision, Lustig saw an opportunity. What if he could make a virtue, even compositional principle, out of latency?" (Lowder 2013).

Continuing my research, I discussed latency technology with Chris Chafe, professor and director of Stanford University's Center for Computer Research in Music and Acoustics (CCRMA). Chris is deeply familiar with latency and technology as one of the core motivators of networked music performance in the United States and author of widely used software for performance over broadband networks.[16] He notes that there is "content that could live at that timescale",[17] and with sufficient vital information of the state of the network, musicians can not only mitigate unreliability with appropriate musical choices but also enjoy the fault-prone means of transmission. Chris's 2001 work *Network Harp*, in which he generated tones using variable network delays, exposes the latency of network through sonification by "constructing feedback loops over Internet connections" (Rohrhuber 2007, p. 154). Chris's application of the networks' vital information to directly inform musical content is an example of finding aesthetic inspiration in the machine, a by-product of the "immersive experience of working in environments suffused with digital technology" (Cascone 2000, p. 12).

4.1.1 Parameters of control

For a successful networked music performance, the core compositional strategy is to accept that latency is elemental to the conditions. Latency over the public network cannot be made shorter until major physics breakthroughs occur.[18] Latency can be either a constant delay or it can be subject to instability, resulting in an inconsistent response time over the network. The compromise between transmission fidelity and latency is integral for the experience of remote presence. Consider the last time you had a video chat call with the other side of the world, latency may have caused you and your conversation partner to talk over each other, and packet loss or dropped calls may have frustratingly interrupted your conversation. In a music setting, such transmission degradation can inhibit performance relationships, triggering decisions to mitigate failure. In general, except when working with the most remote or off-the-grid locations, high-fidelity audio is quite good at being transmitted as long as there is a suitable buffer in place. A buffer's intent is to limit jitter, which is a telemetric measurement of the variability in arrive of packets in relation to each other in time. Given a threshold of acceptable jitter, the buffer is configured according to the connection properties of throughput and latency so that packets are given time to be re-ordered when they arrive late due to the consequences of congested or high-latency transmission networks. Consumer software will manage buffers automatically, which limits functionality available to the musician. Dedicated networked music software, on the other hand, allows the buffer, as well as bandwidth usage—which affects quality, and other properties, to be modified at will.

In conversation with Chris, I asked if he could imagine any advances that would improve the experience of networked music performance and his immediate reply was "I guess we are presuming that speed of light isn't something we've figured out?" (Chafe 2016). On a technical level, while we cannot shorten distances without breaking the laws of physics, we can attempt to stabilise the network, make incremental improvements in the transmission, and work to bring Internet2 services to universities and institutes around the world.[19]

[16] Chris Chafe is a major contributor to the JackTrip networked audio open-source software, which can transmit multiple independent streams of full-resolution audio at very low latencies on high-bandwidth connections (Chafe and Caceres 2009).

[17] Cáceres and Alain Renaud (2008) developed several techniques for playing network feedback with their *Net vs. Net* collective.

[18] With any physics breakthrough that affects space travel and all manner of human activities, music performance will be a much lesser concern for society!

[19] Given that in the early 1990s I was unable to access non-New Zealand websites at my university console due to the sheer cost of international traffic at that time and now I have access to all the world's public data at my fingertips within a few seconds, it won't surprise me if we will all be connected at high speeds and low latencies within our lifetime. Endeavours such as StarLink (https://starlink.com) I hope will prove me right.

The controllable parameters for latency are equally technical and musical. We can adjust the length of latency through technical means (though we cannot shorten it except by coming closer to each other), or we can develop musical responses either composed or improvised that interact with the network latency. Regardless, the composer must understand the networked environment to better develop compositional strategies and make use of the technical solutions available.

4.2 The impossible, multi-located, multi-authorial space

The conditions of latency and the loss of natural human-level exchanges of vital information means that musicians, when connected remotely over a network, cannot use tacitly known physical models of time and space. When reacting together remotely, we experience the "local present, but the networked past" (Robinson 2013). Accordingly, performative expectations must be adjusted. The multi-located space can be exploited by articulating and reproducing spatial properties; i.e. it can be tricked and it can be widened or made smaller. The multi-located space is a reverberant, resonant space, a poly-tonal space that in turn folds back into other spaces. Within that multi-located space, the distinct experience of networked audio lies in the interstitial moments between the unavoidable counterpoint of multiple authors and timelines in which there is "the vantage of being separated. In music we do find advantages like that, [that] sets up kinds of interactions that I don't think we would have with the same players in the same room" (Chafe 2016).

The interaction between remote environments and the immediate climate surrounds us and influences a music's performance towards it becoming a multiplicity that is ever unfolding. I asked Sarah what was different about the networked music medium? Her reply was thoughtful: "the obvious things: latency, spatialisation, wideness of the experience, different aspects of hearing remote performers through the technology which is a different experience than that if they were there in person. On an artistic level, networked audio creates a *wideness* in the music, a wider experience of sound. There's also, within the distance, there's an intimacy about it. I believe that I'm hearing the remote performers through these speakers [in real time] and there's a directness that is different from, say, watching an echo of a stream or recorded video. To be able to connect live and perform together live is a different level of intimacy" (Weaver 2016).

Sarah speaks of her intuitive level in terms of 'synchrony', which could also be thought of in terms of Csikszentmihalyi's concept of flow (Gaggioli et al. 2017). When considered in the context of ensemble performance, flow is a desirable psychological state defined as a "collective state of mind" that occurs when "members develop a feeling of mutual trust and empathy, in which individual intentions harmonise with those of the group" (Sawyer 2003, p. 46). Flow is a state not limited to music, it may be experienced during sports or other activities; i.e. it is a state achieved through the act of performing and may similarly be achieved by a solo actor who is in complete engagement with their own creative process. In the context of networked music performance, achieving flow may be reached though the awareness and interaction with the system's effect on time or it may be achieved through fusing spaces by using harmonic and timbral resonance.

The multi-located space is an impossible space. As opposed to the singular composite space, it is fractured and heterogeneous by nature of separation. With music, we can bind what is detached and artificially bond spaces. Music can draw us in towards each other or it can separate us. Music can be exclusive or inclusive; it can create social space and generate social bonding or it can spur alienation. Nicolas Collins illustrated the way spaces become bonded through networked sound in his five-location network performance Fibre Jelly, "a networked concert where each musician performed in a different space in the ZKM building in Karlsruhe. The musicians listened to and processed each other's sound as part of their own concert. The audience could choose to wander around between the concerts or sit in the main hall and listen to a multichannel mix" (Bennett et al. 2004).

Chris observed that when he remotely engaged with another person in real-time, it "creates a very strong sensation … As soon as it becomes interactive and there is a back and forth element of trust and communication of things … we're in a dance together, and that puts us not specifically on one side or the other, it puts us in a kind of mental meld in the middle which has no physical place" (Chafe 2016). This engagement that Chris describes relates to Csikszentmihalyi's idea of flow where "you get to where you are so absorbed in the music and the music you are making together, that the physical aspect of that just is diminished" (Chafe 2016).

4.2.1 Parameters of control

The projection or reinforcement of mediated sound, whether that is pre-recorded, live on a stage via microphones, or transmitted remotely, inherently involves intent of spatialisation by choosing placement of playback monitors in a certain space. Spatialisation may mean choosing to reproduce a remote space's directionality, or it may involve a combination of decisions such as to merge the remote and composite spaces. Techniques in working with spatialisation and diffusion are well documented in the literature, such as Larry Austin's *Sound Diffusion in Composition and Performance* series (Austin and Field 2001).

One of the key issues when projecting networked sound is the 'Larsen Effect'.[20] Along the resonant spectrum lies the delicate balance between reproduction fidelity and the dangers of acoustic feedback. Once monitors and microphones are switched on and a networked audio connection is made between a similarly monitored space, great attention must be paid to monitor and microphone placement and their levels. The resonant frequencies of the microphone (and a microphone's directionality), amplifiers, room acoustics, codec design, and the dynamic energy between them, e.g. the distance between speakers and microphone, tunes a room, setting the audible experience. This is a technical art that permits manipulation in real time for effect. Once a room is 'well-tuned', the composer should find themself with an instrument where the careful adjustment of levels allows a distinct sonic fingerprint to sound. Participants may also choose to wear headsets for personal and remote monitoring. Using a headset creates yet another space, which is a private, utilitarian space designed for logistical purposes. However, headsets cannot help but inform the performance aesthetic because the participants become isolated from the experience as a whole.

Sound can be completely artificially generated, yet we strive to create meaning. We hear projected sound as sonic energy, as a representation of physical energy from what may be an actual acoustic event that is transmitted and reproduced in some form, or it may be constructed with no relation to an original sounding event. I present three scenarios as examples:

(1) There is no obligation to transmit or reproduce reality as converted to digital form.
(2) A multi-located reality may be experienced as a singular resonant reality or as multiple, disjointed realities.
(3) A local reality has no obligation to interact with a remote reality and vice versa.

Choosing where to have the audience effects how a space is transduced and amplified, and how projection and manipulation of that project can affect the treatment of the remote sound image. What is essential and intrinsic when performing together remotely is the understanding that there is no singular primary experience and therefore no single primary author. Participants each hear a different timeline experience; they are each the primary and secondary authors of their musical interaction. It is a multi-authorial experience that participants navigate by making performance choices. It is not always the case that there will be an audience on each side of the connection. Perhaps a musician or ensemble is beaming in remotely, such as the ensembles in Ray's networked performance, in which case participants may choose to exclusively focus on a fuller musical experience on the audience side. Perhaps there is no audience at all or the audience is similarly remote, such as a distributed web-based broadcast around the world to individual participants; such decisions cannot help but affect a performance.

4.3 Digital mediation

Multi-located networked Internet audio is completely digital. Like digital music, it can be completely simulated (and often is during the developer's testing phase), or it can be a reconstruction of real-world activity. While audio transmission technology generally aims to mask errors, its status as a digitally mediated process allows us to both measure and manipulate the condition of the network.

Fig. 4 shows a visual representation of 10% packet loss (or "drops") in an exaggerated waveform, showing how much audio comprehension can be lost given even a small amount of data loss.

Packet loss is the result of technical failure. Somewhere in the network, congestion has occurred due to heavy traffic, or a route has experienced machine failure due to congestion or software buffer overruns. The spectrum between reliability and failure is in full force with networked audio over the public Internet. Taking influence from the glitch and post-digital aesthetics, the composer may choose to recognise, accentuate and exaggerate failures, or they may otherwise prefer to mask the errors using advanced codec algorithms. During the rehearsals for Latency Canons, Ray found that "it was really hard to stay together under these circumstances so it ended up being this very strange, very unpredictable kind of a mess" (Lustig 2016). This shows that technical decisions cannot always be made during the composition process. Ray had earlier determined that the choice of technology would be an integral part of the outcome: i.e. "the whole ethos of the piece from the very get-go was to let all those problems shape the piece" (Lustig 2016). In my own personal interest in digital aesthetics, I heed the renowned computer scientist Donald Knuth who "expounded on the art inherent in both programming and the program since the 1970s" (Bond 2005, p. 120) and suggested that creative and intellectual satisfaction is found in mastering both the technology and the music that it can produce. Ray's experience is a reminder that the composer can choose to embrace uncontrollable technology by allowing it to shape the result as a critical part of their decision making.

[20] Named after Danish electroacoustic scientist Søren Absalon Larsen who discovered the effect, referring to the "loop established in an electrophonic chain" that "constantly reinjects the signal over itself" (Augoyard and Torgue 2014, p. 65).

4.3.1 Parameters of control

With the development of sophisticated telemetric tools and aids, the parameters of control in the transmission mechanisms offer a wealth of aesthetic decision making leading to a number of methods whereby the composer and musician might manipulate the noisy, error-prone public network for aesthetic means, and exploit how data transmission via packet networks adds uncertainty to the communication channel.

To transmit data, that data is split into small pieces called 'packets'. A 'switched' network, such as Internet2 or digital ISDN, creates a dedicated line between two locations; therefore the latency is the same for each packet. When using packet networks, upon which the public Internet is made of, the latency changes each time a piece of data is sent over a network. The public Internet is a network of many packet networks. The data packet leaves your device and is sent to your ISPs network, from where it will be forwarded on to its destination. The packet is sent to the next network location or 'hop', and may go through several, often 10 or 20 hops, before it arrives. At each hop, the best route is examined: perhaps there is sudden congestion at the next hop, so it will send your packet via a different route. As a result, packets take different, non-predetermined routes, and at each hop the congestion may drop or increase or hops may even go offline at any moment due to failures, leading to variable routing times depending on the quality of the route. What might be 100 ms on the previous route may now be 105 ms. There may be more or fewer packet losses at any given time. These changes can all occur quickly and without warning. To obtain a sufficient level of comfort for participants, where network errors and latency cannot be averted, we can put in place mechanisms to share information about the status of the network and send status and control messages about the music we play together. By using telemetrics and simple messaging, a complex set of rules can be implemented for creative purposes.

5 New aesthetic challenges

Latency and uncertainty, the multi-located and multi-authorial spaces, and digital mediation are inseparable from networked music performance which is a complex system based on the interaction of protocols which are often overlooked as having manipulatable parameters. The primary characteristics expose networked music performance as latent and uncertain, multi-located and multi-authorial, and digitally mediated, qualities that are distinct to and inseparable from networked music performance. Flowing from the discovery and analysis of the causes of these primary characteristics was the development of four aesthetic approaches towards a virtuosity of expression in networked music performance: post-vertical harmony, the effects of the network on performative distance relationships, new resonant timbres through the collision of multiple spaces with transmission technology and the post-digital aesthetic.

The music philosopher Lydia Goehr sees music not only as an auditory phenomenon, but also sees music as in the making, as being produced. Goehr (2003) asks, what we are doing when we engage in a musical way? By focusing on the institutions and systems within which we produce music, we expose the technology, the mechanics of that technology and conventions of behaviour, i.e. the expectations that are formed, when we use that technology. If we are to embrace the technology that permeates our lives, we are to embrace a musical exploration of the properties of that technology, which are properties of a system born from the technological inventions and compromises driven by the human need to address our innate social need for communication. It is through the exploitation of technology's properties that the composer can articulate the tangled relationship of unstable, latent transmission, with the appeal to participants to experience presence through networked mediation. While we gloss over the disengagement that the technology we use to transmit digital presence tends to create in participants in the production of the work as a whole, revealing the finer grains of the network technology integrates the music better with the notes on a page for a more meaningful experience.

The relationship between the cause and effect of our experience when composing music during the nascent stages of creativity, when a new aesthetic is being explored, is an embodiment of musical creativity as a cognitive and performative causality (Nagy 2016). Stylistically, the scope for aesthetic expression is gigantic here although Meyer (1989) notes that "most changes in Western music have involved the devising of new strategies for the realisation of existing rules, rather than the invention of new rules" (p. 20). It stands to reason that early interpretations of networked music performance will be reinterpretations of existing musical structures, pending technological developments that address the need for tools that aid in realising complex remote relationships. While early forms of sophistication in new musical forms are derived from existing skill-sets, Norman et al. (1998) appeal to the musician-technologist that she must seek to capture the "skill and imagination and expressiveness of a performer" by creating an instrument that can be approached with virtuosity. On a technical level, this can mean developing new systems such as multi-located tuning guides, predictive latency synthesis engines and designing new integrations with dynamic scores and time-keeping systems that respond to network and participant conditions. We can use technology to generate live manuscripts that match note durations to real-time latency, which allows predetermined harmonic progressions by

embedding critical vital information for performance precision. As we improve our understanding of the spectral neurological effects of latency or the effect on pitch responses due to variations of frequency and spectral envelopes, and device communication, we can write more-sophisticated scores and build more-sophisticated machines that can interact with us. For example, the composition series F not F[21] uses machine learning technology to recognize certain musical phrases, which when detected in real time during a performance-transmitted events to each remote location of the performance. The musicians, who otherwise may not have distinct per-musician audible information due to timbral fusion, are informed by a responsive digital score not only what is played by their remote peers but even if they play the same musical material at the same time. It is possible to create ways of performing together in time even when musicians are not only out of sync due to latency but cannot even detect the intentions of any other individual musician in the ensemble.

The approaches and strategies discussed in this text are not necessarily limited to networked music as a genre because creative minds readily remap novel technologies and creative approaches to other forms of expression. For example, we might consider latency and instability as technical devices and envision interfaces where such properties can be manipulated beyond their physical constraints, or even embody those constraints as core, purposeful characteristics. We might consider the inability to know what another is doing to be dependent on the interfaces we use to interact: many of the same musical challenges affect digital ensembles as well as networked ensembles.

Virtuosity of expression in digital and networked music means exploring how participants respond, both to each other and to other spaces. It means exploring how a score can be musically expressive while transmitting the vital information needed for synchronisation. It means accepting that there is no singular experience because the network shatters any notion of synchronisation as being anything but an illusion, as "time itself has meanwhile turned out to be a multiplicity" (Rohrhuber 2007, p. 154). How can musicians best make transparent the fact that simultaneous events are occurring and different experiences are being formed? What happens when the technology we use disrupts reproduction fidelity or fails completely? This means designing for uncertainty, developing musical content "that lives at that timescale" (Chafe 2016), and conceiving of music that illuminates the distance between us, music that draws us together.

[21] *F not F,* (Wilson 2019). Performed for two pianos at the Orpheus Institute, Ghent, March 2019, for two ensembles at the TENOR conference, Melbourne, July 2019, and for two pianos at the Web Audio Conference, Trondheim, December 2019. Both performers and audience commented how the real-time information displayed on the electronic score was helpful to knowing the state of the remote performer.

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