# Lovelace's Legacy: Creative Algorithmic Interventions for Live Performance

David De Roure
Oxford e-Research Centre
University of Oxford
Oxford UK
david.deroure@oerc.ox.ac.uk

Pip Willcox
Oxford e-Research Centre
University of Oxford
Oxford UK
pip.willcox@bodleian.ox.ac.uk

Alan Chamberlain
Department of Computer Science
University of Nottingham
Nottingham UK
alan.chamberlain@nottingham.ac.uk

## ABSTRACT

We describe a series of informal exercises in which we have put algorithms in the hands of human performers in order to encourage a human creative response to mathematical and algorithmic input. These 'interventions' include a web-based app, experiments in physical space using Arduinos, and algorithmic augmentation of a keyboard.

## CCS CONCEPTS

• Applied computing~Sound and music computing • Applied computing~Performing arts • Human-centered computing

## KEYWORDS

Ada Lovelace, algorithmic composition, Analytical Engine, Arduino, creative computing, experimental humanities.

## 1 Introduction

Over the past three years we have conducted a series of informal exercises in which we have put algorithms in the hands of human performers and audiences. While these exercises take various forms, the common endeavour is to encourage a new human creative response to the mathematical or algorithmic input. As such, our work plays into the conversation about the creative relationship between human and machine, and mathematics and music.

The work began through a study of Ada Lovelace, who wrote about computers and creativity in 1843. We discuss this background in the next section. Section 3 then summarises five of our interventions: our Web-based "Numbers into Notes" application, used for a performance at Audio Mostly in 2017, then three instantiations on the arduino open-source hardware platform, and finally our "algorithmic arpeggiators". We close with a discussion of ongoing work.


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## 2 Background

A major symposium was held in Oxford in December 2015 to mark the 200th anniversary of the birth of Augusta Ada Byron, known now as Ada Lovelace through her marriage. Lovelace was trained as a mathematician and collaborated with the engineer-polymath Charles Babbage as he designed the Analytical Engine, an important but hypothetical general-purpose computer which today would be described as Turing-complete. Arising from this work, Lovelace is often credited with publishing the first program for computers as we know them today.

Her writing is significant in revealing insights into computing ahead of her time, looking to a future where machines would be needed that could outperform even the proposed Analytical Engine. Her thinking clearly transcends the immediate ambition to perform mechanical calculations. In her extensive additional notes to the 1843 translation of a publication of a lecture by Babbage [1], Lovelace wrote about computers and music:

> "Supposing, for instance, that the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptations, the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent." (note A in [1]).

Still frequently quoted today within the computers and music domain, Lovelace's notes are also cited in debates around computers and creativity, notably by Turing in the "imitation game" paper [2] and, in turn, Margaret Boden in her "Lovelace questions" [3]. For example Lovelace wrote:

> "The Analytical Engine has no pretensions to *originate* anything. It can *do whatever we know how to order it* to perform. It can follow analysis; but it has no power of anticipating any analytical relations or truths. Its province is to assist us to making available what we are already acquainted with." (note G in [1], Lovelace's emphasis).

Our contribution to the symposium arose from a thought experiment: had Lovelace lived longer, and had Babbage successfully built the Analytical Engine, what might have happened in pursuit of Lovelace's observations? Also, how would Lovelace respond to computing today? This was the motivation for our sequence of experiments and demonstrations.

An important influence, in a sense the first algorithmic intervention, is due to composer Emily Howard. As part of the anniversary celebrations, Howard conducted performances by musicians from the Royal Northern College of Music of one part of her Lovelace trilogy, 'Ada sketches' [4]. By background Howard is a mathematician and computer scientist, and uses mathematics in her compositional process. The performances, at the Science Museum in London and then in Oxford, had a distinctive format in that they were accompanied by an explanation of the music by Howard and of the mathematics by Lasse Rempe-Gillen (University of Liverpool), and subsequently the audience was invited to turn 'Numbers into Notes' using simple algorithms.

# 3 Five Algorithmic Interventions

## 3.1 Numbers into Notes

Babbage's Analytical Engine remains unconstructed to date, but we can simulate the execution of programs on it digitally, based on the detailed accounts of the Engine's design provided by Babbage, Menabrea, and Lovelace. In our first experiment, which was presented at the Ada Lovelace Symposium, we set out to generate a number sequence that could then be performed as music, perhaps mechanically or by human players.

Our hypothesized workflow was that the Analytical Engine would run a parameterised program to generate a number sequence, and parts of this sequence would then be given to different instruments. Inspired by the use of punched cards in the Jacquard loom and in the proposed Analytical Engine, we envisaged 'piano rolls' generated by the engine. The numbers are strictly faithful to nineteenth-century mathematics, while human intervention decides the algorithmic parameters and the mapping of the numbers to notes and instruments.

We made a decision at this point to use a Fibonacci sequence for demonstration purposes as it is well known, and we took advantage of the mathematical property that reducing a Fibonacci sequence using modulo arithmetic results in a periodic sequence, as noted by Lagrange in 1774. This is called the Pisano period (see https://oeis.org/A001175). For example, when Fibonacci sequences are reduced modulo 5 through to 128 (being the range of numbers of notes we might work with), the Pisano period varies between 10 and 500, with a higher number of occurrences of shorter periods. We have continued to use the Pisano period as a reference algorithm in all our implementations.

For the demonstration we used the Fourmilab simulator (https://www.fourmilab.ch/babbage/contents.html) by John Walker, which is a Java program that simulates the Analytical Engine. Walker notes that since the Analytical Engine was never built, it is not possible to provide an authentic emulation, but rather a simulation based on the available designs. A more recent version of the simulator which runs in a browser (using HTML5 and JavaScript) is now available.

Learning to use the simulator requires understanding the nomenclature of the Analytical Engine (such as the notions of analyst, attendant, cards, mill, store, and printer) but otherwise is not dissimilar to the assembly language programming that was taught over two centuries later. While the steam-powered machine would have been slow, it did not lack precision: the 1837 description of the Engine had 40 decimal digit capacity in the "Store", and the "Mill" could accommodate the 80 digit product of two numbers. Babbage's later account in his memoirs describes 50 and 100 digit capacities respectively [5].

We generated sequences with all numbers mapped to notes (e.g. using chromatic or diatonic scales), and then with a variety of audiences we asked people to identify musical themes that they picked out. We defined the number and time ranges to isolate these themes and mapped them to different instruments using the Logic Pro digital audio workstation (DAW) software. This enabled us to use high quality samples of instruments similar to those used in Lovelace's time. We have produced several pieces of music in this way, and our demonstration theme, which is based on Fibonacci mod 35, has also been used as a basis for a jazz number.

The success of the simulator demonstration encouraged us to produce an interactive tool which would enable people to conduct their own explorations, using a variety of algorithms, to stimulate discussion of mathematical calculations on the Analytical Engine, contemplating what Lovelace and Babbage might have done at the time if the engine had been built. The single page web app was coded in JavaScript using HTML5 Web Audio, and was launched in 2016 (available on http://numbersintonotes.net). The tool generates a musical score, midi, and a provenance graph which describes how the algorithmic music fragment was obtained, as shown in Figure 1. Our attention to provenance resonates with another note from Lovelace:

> "Were it otherwise, the engine could merely compute the arithmetical nth function, a result which, like any other purely arithmetical results, would be simply a collective number, bearing no traces of the data or the processes which had led to it." (note E in [1]).

The web app was subsequently used in a third recital of Emily Howard's 'numbers into notes' event, at the Royal Northern College of Music in 2017. Chamberlain used the software to provide the soundtrack for an award-winning film[1]. In August 2017 we performed a live composition entitled "The Gift of the Algorithm: Beyond Autonomy and Control" based on fragments produced by several contributing musicians using Numbers into Notes. The piece was performed live at Oxford House, London, UK in August 2017, in conjunction with the Audio Mostly 2017 conference. Using Ableton Live as a live instrument, Chamberlain set out to explore concepts around crowdsourcing, social machines and composition [6], challenging the boundaries of the traditional composition and performance process.

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[1] *See*: The Science of Music Brought to the Big Sceen - http://blogs.nottingham.ac.uk/newsroom/2018/03/12/science-music-brought-big-screen/

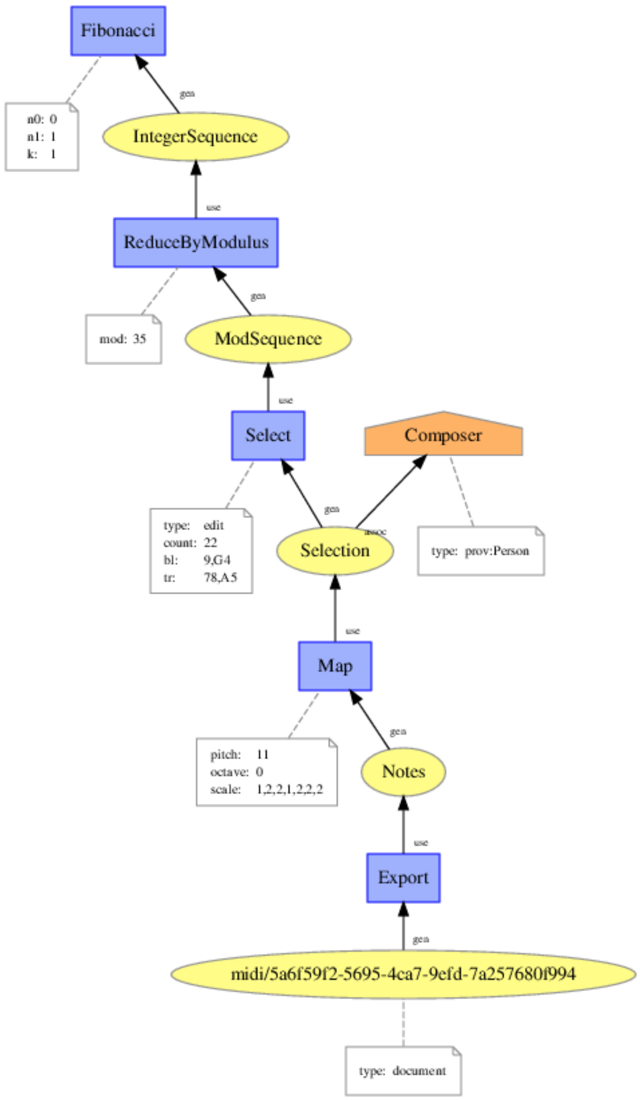


**Figure 1: Provenance graph for Fibonacci modulo 35**

## 3.2 The Arduinos

Our next set of interventions bring Numbers into Notes into the physical word, with "Arduino analytical engines". Using Arduino open source single-board microcontrollers, with a slave audio processor and amplifier to drive speakers, we replicated the Numbers into Notes tool as a small standalone "music engine". 50 decimal digits of precision aside, today the algorithms run readily (and, for music purposes, in real time) on the processors of the range of open source Arduino hardware, such as an 8-bit microcontroller, or 32 bit ARM.

*3.2.1 Space.* We built five of these engines, using first generation Arduinos, with a variety of sensors to influence the parameters to the algorithm. They were deployed in a physical space, so that people could interact with them to configure the algorithms. Nicknamed the "Fibonacci Orchestra", we exploited the musical outcome of our earlier work mapping the output of the Analytical Engine simulator: multiple sequences played alongside each other generate harmonies, and this effect is richer when sequences are played at different but geometrically related tempos. This was demonstrated at Mobile HCI in 2016 [7] and is reported in [8]. Again, we challenge traditional boundaries, because the musical experience is essentially configured by the audience. We also developed a simulator, using Netlogo, to simulate music generation with different numbers and configurations of devices, reported in [9].

*3.2.2 Gifting.* Subsequently we ran the same algorithms on the "Teensy" device, which has a much smaller form factor (1.4 x 7 inches). The model we used, a Teensy-LC, provides an ARM Cortex-M0+ processor running at 48 MHz. Significantly this device natively supports MIDI over USB, which means the devices, which are as small as a USB memory stick, can be plugged directly into any USB interface that is expecting a MIDI keyboard. Our informal intervention has been to plug these devices into other music performance demos, as a kind of algorithmic keyboard player. This was demonstrated in the "Interaction, Instruments and Performance: HCI and the Design of Future Music Technologies" workshop at Audio Mostly in 2017, with 8 teensies preset to different algorithmic parameters and used in combination. These teensies have since been given away, or in other words we have distributed our algorithms to colleagues in physical form, for use in a variety of demonstrations. An unanticipated outcome of this intervention is this social "gifting" behaviour, whereby people can give algorithms to others as physical gifts and they can be passed on.

*3.2.3 Fibonacci Theremin.* This line of thinking, where we were adding algorithms to equipment used in performance, led to the development of an Arduino device with Theremin controls. The software previously used for the Fibonacci orchestra (2.2.1) was adapted for the open hardware Theremin (http://www.gaudi.ch/OpenTheremin). In a standard Theremin, two metal antennas sense the relative position of the performer's hands, controlling oscillators for frequency and amplitude. The Fibonacci Theremin maps the two antennae to algorithm parameters. A particularly effective mapping enables the theremenist's hands to describe which part of the algorithmic output is audible, which gives the sense of 'playing the algorithm' in space. The innovation in this intervention was to present the Arduino as an algorithmically augmented instrument for use in live performance.

## 3.3 Algorithmic Arpeggiation

The most recent intervention has been to make our algorithms available through an existing (and highly established) musical instrument: a piano keyboard. The ambition is to facilitate creative use of the algorithms during performance, by creating a new kind of instrument that is in part automated mathematically. We achieved this by coding the algorithms in JavaScript which we run in the Logic Pro DAW, using the "Scripter" plugin. The

Scripter processes incoming MIDI and/or timing data, and this processing occurs ahead of any audio generation. Hence the scripts can respond to incoming note events and transform them.

Our first Scripter experiment, called "Fibber", used the Fibonacci sequence, so that pressing a key triggered a sequence according to predefined parameters. The sequence decays and the number of notes depends on the velocity at which the key is pressed. In particular this interface lets the performer play one sequence against another and experiment with multiple simultaneous sequences, starting on different notes and with various timings, also using different instrument samples. In use this feels like playing a sampler, but each sample is being generated algorithmically in real time. By mechanical analogy, it is as if pressing each key spins a disk which generates a sequence.

Our second Scripter experiment was the "Algorithmic Arpeggiator". This uses algorithms to generate notes selected from the set of keys depressed simultaneously, where the order is chosen according to the algorithm. The particular algorithm of interest in this experiment was a permutation algorithm designed to replicate bell-ringing practice, drawing on the important 1668 work *Tintinnalogia, or, the Art of Ringing Wherein is laid down plain and easie Rules for Ringing all sorts of Plain Changes* [10]. This book provides a comprehensive introduction, which is scientific in style.

In contrast to MIDI arpeggiators, which take a chord and produce a rapid series of notes based on that chord over multiple octaves, the algorithmic arpeggiator has a pass through mode whereby keys pressed are sounded immediately and continue to sound by algorithmic selection as long as the keys are held down. This gives the performer a degree of creative control, as if they and the algorithm were performing together. Again, it is as if a mechanical selector is running behind the scenes.

These mechanical and mathematical metaphors go back to Lovelace, and the inspiration that Babbage drew from the Jacquard loom, operated by punch cards. Lovelace wrote:

> "The distinctive characteristic of the Analytical Engine, and that which has rendered it possible to endow mechanism with such extensive faculties as bid fair to make this engine the executive right-hand of abstract algebra, is the introduction into it of the principle which Jacquard devised for regulating, by means of punched cards, the most complicated patterns in the fabrication of brocaded stuffs… We may say most aptly that the Analytical Engine weaves algebraical patterns just as the Jacquard-loom weaves flowers and leaves." (note A in [1]).

An extension of this work would be to use a Disklavier—an acoustic piano fitted with sensors in order to record the precise movements of keys, and also with electromechanical solenoids to press keys automatically as in a self-playing piano (pianola). Benford et al have developed a related system for recognising and responding to musical trigger phrases [11].

## 4 Ongoing work

Alongside this work our team has also been engaged in the collaborative development of an IoS and Android app which enables us to capture audience perception of aspects of a musical performance. Designed in conjunction with PRiSM (the RNCM Centre for Practice & Research in Science & Music), the app was used in January 2018 at a performance by the Oxford Philharmonic of Haydn's Symphony No. 47 in G major ("The Palindrome"), presented by Marcus du Sautoy, to see if the audience could detect palindromes. This work complements our algorithmic interventions in that it addresses the perception of mathematics and algorithms in music.

The Numbers into Notes software has been extended to generate multiple output formats, including MEI (Music Encoding Initiative), in addition to score, MIDI, and the W3C Provenance standard (PROV). It has become a useful data source for generating fragments used in testing other music tooling, particularly in the semantic music arena: it is a kind of "semantic signal generator". In particular it is being used in the development of the SOFA (SOFA Ontological Fragment Assembler) system, which builds also upon the MELD (Music Encoding and Linked Data) tool to augment and extend MEI structures with Semantic Web Annotations capable of addressing musically meaningful score sections [12]. Together these tools are being used to demonstrate the concept of processing and re-composition of Digital Musical Objects (DMOs).

Returning to the original thought experiment, we have been exploring the incorporation of electromechanical techniques with the Analytical Engine, as electromechanical systems were becoming established at the same time as Babbage was seeking funding: Charles Wheatstone, an acquaintance of Lovelace and Babbage, patented the telegraph system in 1837, and a successful system was installed on the Great Western Railway over a 21km distance in 1838; only two decades later the first transatlantic telegraph cable was in place. This extends the backdrop to our discussion as to might have happened next. To understand the design of the Cooke and Wheatstone needle telegraph, and its potential applications, we have built prototypes and designed new interfaces, looking at it by analogy with musical instruments (as Wheatstone himself might have done). This is an example of a methodology we are calling experimental humanities [13].

## 5 Conclusion

In this paper we have summarised a series of creative interventions, inspired by Lovelace and achieved through digital prototyping. The interventions cut across multiple boundaries: the composer and performer, performer and audience, and human and machine. They also suggest new forms of algorithmically augmented instruments. We look forward to a future of human and machine co-creation.

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