likely music

Probabilistische Musiknotation

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Zusammenfassung

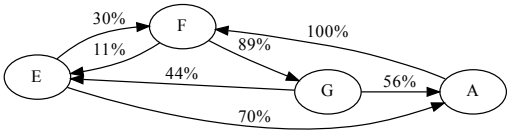
likely music ist eine Software, um probabilistische Musik zu notieren und abzuspielen. Probabilistische Musik bedeutet in diesem Falle, dass die Interpretation der vorliegenden Notation deutlich freier ist als bei herkömmlicher Musik und auch die Reihenfolge der Noten betrifft. Um dies zu erreichen, wird ein eigenes Modell von Musiknotation verwendet. Anstelle von linearer Reihenfolge von Noten bzw. Akkorden tritt ein gerichteter Graph, in dem die Noten (bzw. Akkorde) die Knoten und die möglichen Übergange zwischen diesen die Kanten darstellen, wobei jeder Kante eine gewisse Wahrscheinlichkeit zugeordnet ist. Dieses Modell ist unter anderem sehr gut von einem Computer zu fassen, wodurch es möglich ist, solche Notationen automatisch zu „interpretieren“ oder abzuspielen: Eine konkrete Notenabfolge wird gemäß der Notation ausgewürfelt.

Die Software *likely music* kann sowohl probabilistische Noten erstellen und editieren, als auch mittels MIDI diese abspielen oder als Audiodateien exportieren.

Idee

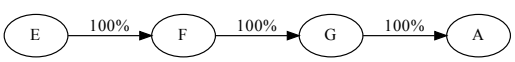
Der eigentlichen Idee ging ein mehr oder minder gescheitertes Projekt für diesen Wettbewerb voraus. Im Frühjahr diesen Jahres entschied ich mich, dieses – eine Demo [1] – abzubrechen, einfach weil ich befürchtete, es nicht bis zur Frist fertigstellen zu können. Die Motivation für dieses Projekt speiste sich aus meiner Faszination für Demos an sich, denn ich hatte mich bereits im Vorfeld öfters mit diesen beschäftigt und beim Ansehen der Einsendung von Demo-Wettbewerben ein Bedürfnis entwickelt auch eine zu entwickeln. Das neue Projekt speiste sich aus einer weiteren Faszination von mir, nämlich einer für Kunst, die durch Zufall entsteht. Ich erinnere mich besonders oft an Kunstinstallationen, die ihr gestaltendes Element durch Zufall, einen undurchschaubaren oder chaotischen Prozess bezieht. Beim Nachdenken über Zwölftonmusik, die – meiner Meinung nach – ein wenig jenen Elements hat, kam mir die Grundidee für *likely music* – wie ich mich erinnere – auf dem Gang zwischen zwei Schulstunden: Nämlich ein Modell, um Musik zu beschreiben, die zufällig im Vortrag ist.

Das Modell, das ich aus Angst, es zu vergessen, mehrmals aufschrieb, sieht Musik als gerichteten Graphen, wobei die Knoten Musiknoten einer bestimmten Länge und die Kanten zwischen ihnen die Wahrscheinlichkeit des Wechsel von der einen Note zu anderen sind. Vorstellen kann man sich es in etwa wie in der folgenden Grafik.



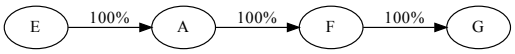
In diesem konkreten Graphen sind die Noten E, F, G und A als Knoten vertreten (der Einfachheit halber sind die Notenlängen weggelassen). Beispielsweise vom E führen zwei Kanten weg, eine zum F mit dreißigprozentiger Wahrscheinlichkeit und eine zum A mit siebzigprozentiger Wahrscheinlichkeit, d. h. nach dem E kommt in sieben von zehn Fällen das A und in den drei übrigen das F. Analog verhält es sich mit den anderen Noten.

Diese Darstellung ist in gewisser Weise auch nur eine ausdrucksstärkere Form einer normalen Notation, denn ein Weg durch den obigen Graphes könnte so aussehen:



Diese Interpretation, die eine Wahrscheinlichkeit von ca. 15% hat, entspricht einer einfachen, linearen Notation, wie sie in einem Gesangsbuch ste-

hen könnte. Wir sehen also, dass solche probabilistiche Noten (wie unser Graph von vorhin) durch ein Verfahren, das ich einfach in einer Erweiterung des Begriffs als Interpretieren bezeichne, auf eine lineare Notation reduziert werden können, die mit einem Instrument oder vom Computer gespielt werden können. Es ist sogar nicht nur eine lineare Notation, sondern – je nach vorgegebenem Graph – eine Vielzahl ihrer möglich. Beispielsweise wäre eine weitere:



Ähnlich enthält der ursprüngliche Graph weitere Möglichkeiten von klassischen Tonabfolgen. Insofern stellt eine probabilistische Notation eine ausdruckstärkere und mächtigere Notation dar, da sie beliebig viele klassische fassen kann.

Zu beachten ist bei den beiden Beispielinterpretationen noch: Sie sind nach vier Noten abgeschnitten, denn, da von jedem Knoten mindestens eine Kante ausgeht, könnte man den Graphen potentiell unendlich lang ablaufen und würde somit eine unendlich lange Interpretation generieren.

Was aus dieser Grundidee zu machen war, schien mir von Anfang an recht klar: Als Software implementieren, um ein graphisches Interface bereitzustellen, das es erlaubt, probabilistische Notation zu erstellen, zu editieren und abzuspielen.

Umsetzung

Gleich zu Beginn war klar, dass Haskell die Programmiersprache der Wahl werden sollte. Sie ist die Sprache, die ich in den letzten Jahren am aktivsten verwendet habe und mir einiges bietet: Statische Typisierung, um Fehler vorzubeugen, ein expressives Typsystem, das es erlaubt, Daten besser zu strukturieren, und funktionale Programmierparadigmen, die sich für mich sehr natürlich anfühlen und das Testen von Programmen erleichtern, um einige Vorzüge zu nennen.

Zunächst konzentrierte ich mich darauf, den Graphen und den Interpretationsalgorithmus als Bibliothek zu implementieren. In der ersten Iteration dieser Bibliothek, noch *probable music* genannt, begann ich auch einen eigenen Softwaresynthesizer zu implementieren, der flexibel auf verschiedenen Plattformen und zu verschiedenen Zwecken verwendet werden kann. Der Synthesizer konnte jegliche Darstellungen von Klängen, Tönen oder Musik dank flexibler Architektur in tatsächliche Töne bzw. Audiowellen umwandeln. Dies ergab interessante Möglichkeiten, sich außerhalb des Zwölftonsystems zu bewegen. Die Tonerzeugung basierte dann auf einer freien Monade [2], die die Instruktionen ›Warten‹ und ›Abspielen‹ kannte. Indem man diese Instruktionen für verschiedene Audiosystem, wie SDL [4], Jack [3] oder auch Audiodateien wie WAV [5] implementierte, konnte man verschiedene Plattformen unterstützen. Allerdings gestaltete es sich schwierig, einen gut klingenden Synthesizer zu schreiben, denn die Messlatte ist im Vergleich zu realen Instrumenten hoch. Hinzu kamen noch einige Performance-Probleme mit meinem maschinennahen Audio-Code.

Also entschied ich mich, die Library vor allem auf den Graphen und die dazugehörigen Algorithmen zu fokusieren und zur Tonerzeugung eine geeignete Abstraktion zu verwenden, um diese zu vereinfachen. Ich habe hierfür MIDI gewählt, eine Technologie, die schon lang in allen Arten von Software und Hardware zur Musikproduktion verwendet wird. MIDI basiert auf einer Abfolge von zeitlich abgestimmten Nachrichten, wie zum Beispiel ›Note C an‹ oder ›Note C aus‹. Aufgrund dieser Nachrichten kann man die Erzeugung und das Abspielen von Musik zwischen mehreren Programmen aufteilen. Außerdem erlaubt es, die bereits existierende Infrastruktur für MIDI-Verarbeitung zu verwenden, die sehr beachtlich ist. Für MIDI verwendet *likely music* die Open-Source-Bibliothek Euterpea[1] [8], die unter anderem eine kleine Abstraktion über MIDI enthält. Sie erlaubt es, in einem internen Format Musik zu konstruieren und anschließend als MIDI zu exportieren bzw. an ein anderes Programm zur Weiterverarbeitung zu schicken.

Bei der Darstellung des Graphen habe ich mich vor allem darauf konzentriert, den Interpretationsalgorithmus, also das (zufällige) Ablaufen des Graphen, möglichst effizient zu gestalten. Da es sich

[1] Ich musste allerdings aufgrund von Inkompatibilitäten mit den aktuellen Haskell-Paketen diese selbst beheben [9]. Diese Änderung wartet [10] aktuell (Stand 23.09.2017) darauf, vom Hauptentwickler in den Code von Euterpea übernommen zu werden.

um einen gerichten Graphen handelt, ist es besonders wichtig zu wissen, wohin man von einem gegebenen Knoten aus gelangen kann bzw. welche Kanten von einem Knoten weggehen. So gelangt man in unserem Beispiel aus dem vorherigen Kapitel vom Knoten mit dem E zu den Knoten mit F und A. Es muss also möglichst effizient sein, die Kanten nachzuschlagen, die von einem Knoten *wegführen*. Mit der Datenstruktur *Map* [11] (im deutschen Sprachgebrauch typischerweise *assoziative Datenfeld* bzw. *assoziatives Array*) kann man genau das sehr leicht realisieren: Man verwendet die Knoten als Schlüssel und eine Liste von Kanten, die vom Schlüssel weggehen, als Elemente. Wenn der Algorithmus nun einen Knoten nachschlägt, erhält er direkt die Kanten, die von diesem Knoten weggehen und somit auch die nächsten möglichen Knoten. Dies ist die einzige Information, die in jedem Schritt benötigt wird. Die Operation des Nachschlagen hat in einem *Map* die Komplexität $O(\log n)$ [12], d. h. die Zeit, die benötigt wird, um ein Element nachzuschlagen, steigt mit dem Wachsen der Datenstruktur logarithmisch (d. h. weniger starkes Wachstum als linear!). Damit bleibt auch das Interpretieren großer Graphen ziemlich schnell. Der Code für die Datenstruktur findet sich im Abschnitt Library, Zeile 30 bis 43.

Der Interpretationsalgorithmus selbst ist rekursiv [15] gestaltet und findet sich in der Funktion `interpretation`, siehe Abschnitt Library, Zeile 52 bis 60. Diese Funktion benötigt einen initialisierten Pseudozufallszahlengenerator [13, 14], den zu interpretierenden Graphen in der eben besprochenen Datenstruktur und einen Startknoten. Nach Ablauf der Berechnung gibt die resultierende Interpretation im MIDI-Format von Euterpea [8] zurück. Zunächst wird der Startknoten im Graphen nachgeschlagen, so werden die Kanten bzw. die nächsten möglichen Knoten erhalten. Nun gibt es zwei Möglichkeiten für den weiteren Verlauf:

1. Es gibt keine Kanten, die von diesem Knoten ausgehen. Also wird die bisher generierte Interpretation einfach zurückgegeben, die Funktion terminiert.

2. Wenn es eine oder mehr Kanten vom Knoten aus gibt, wird eine (reelle) Zufallszahl zwischen 0 und 1 berechnet und mittels der Hilfsfunktion `edgeForRoll` (siehe Abschnitt Library, Zeile 62 - 67) die Kante erhalten, die gemäß des zufälligen Ergebnis als nächstes abgelaufen werden soll. Nun ergibt sich das gleiche Problem wie zu Beginn der Interpretation: Man kennt einen Knoten und will wissen, wie es weitergeht. Also wird nach der Ermittlung des zweiten Knotens die MIDI-Nachrichten aus dem Startknoten extrahiert und dann der Interpretationsalgorithmus nochmal bzw. rekursiv aufgerufen – nur mit dem Folgeknoten als Startknoten. Dessen Ergebnis wird an die aktuellen MIDI-Nachrichten angehängt, was jener Aufruf auch seinerseits wieder macht. So entsteht rekursiv eine (potentiell unendliche) Verkettung von MIDI-Nachrichten, die letztlich die finale Interpretation ergeben.

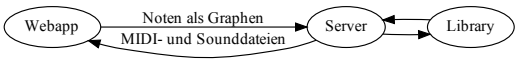
Da die meisten Graphen vermutlich vollständig untereinander verbunden sein werden, wie zum Beispiel der Beispielgraph im ersten Abschnitt, entstehen unendlich lange Interpretationen. Diese zu erstellen benötigt natürgemäß natürlich auch unendlich viel Zeit – der Interpretationsalgorithmus terminiert also nicht. Die einfache Antwort auf dieses Problem ist die Begrenzung der Länge der Interpretation auf eine gewisse Anzahl von Noten, was sich dank eines Sprachfeatures von Haskell – Lazy Evaluation [16] – leicht umsetzen lässt. Denn mit Lazy Evaluation wird nur das berechnet, was im Moment benötigt wird. Somit werden zum Beispiel nur die ersten vier benötigten Noten berechnet und nicht die unendlich vielen die eigentlich noch darauf folgen würden – genau dies wird durch die Funktion `takeNotes` (siehe Abschnitt Library, Zeile 79 - 86) realisiert.

Nun können wir probabilistische Musik in Graphen darstellen, diese automatisch interpretieren und dank Euterpea nach MIDI exportieren. Was fehlt, ist eine angenehme Benutzerschnittstelle.

Zur Technologie für die Benutzerschnittstelle gab es für mich folgende Überlegungen: Zum einen sollte es leicht portabel bzw. auf jedem System laufen sowie außerdem einen begrenzten Entwicklungsaufwand mit sich bringen, damit es bis zum Einsendeschluss auch fertig sein würde. Ich selbst entwickle meine Software auf GNU/Linux, aber zur Abgabe müsste es auf macOS und / oder Windows laufen. Alle größeren Frameworks für Graphische Interfaces für GNU/Linux, wie zum Beispiel Qt [21] oder GTK [22], laufen auch auf den anderen großer

Betriebssystemen. Allerdings bin ich nicht besonders vertraut mit irgendeinem dieser Frameworks. Außerdem war ich mir nicht sicher, wie stressfrei die Verwendung dieser von Haskell aus sein würde (denn klassischerweise verwendet man C oder C++). Also entschied ich mich *likely music* als Webapplikation, die einfach in gängigen Browsern läuft, zu implementieren. Das hat einige Vorteile für mich, unter anderem, dass es leicht zu testen ist, weil die Browser eigentlich überall gleich sind, und, dass ich schon einige Erfahrung in Webentwicklung hatte.

Allerdings hatte ich die Library schon in Haskell implementiert, in Browsern läuft aber nur JavaScript (ohne größeren Aufwand zumindest). Also musste ein Programm her, um die Kommunikation zwischen der Library und der Webapplikation zu realisieren. Ich entschied mich für eine Client-Server-Architektur [17], also einen Server, der die Interpretation und den Export von Sounddateien für den Client, also die Webapplikation, übernimmt. Der Client wiederum müsste sich ausschließlich um ein ansprechendes Interface kümmern. Die ungefähre Gesamtarchitektur sieht also nun so aus:



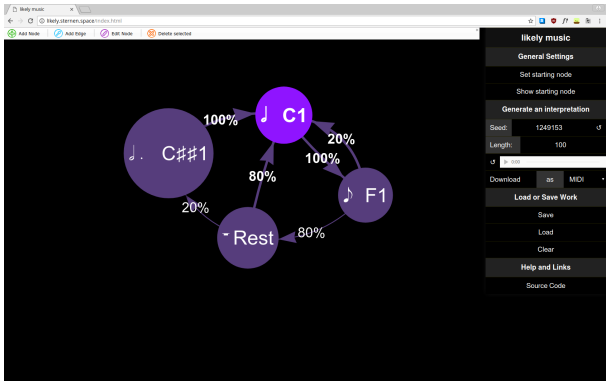
Der Server basiert auf den Libraries servant [18] als Webframework. Wie im Abschnitt Backend zu sehen, besteht das Serverbackend aus zwei Dateien Quelltext: In `Api.hs` wird die Struktur der REST-API [19] definiert, mittels der die Webapplikation mit dem Server kommuniziert. Der Server bietet folgende Funktionalität an:

- `/interpretation/mid` An diesen Endpunkt schickt die Webapplikation einen Graphen plus einiger Parameter in Form von JSON [20] und erhält eine Interpretation auf Basis des Algorithmus als MIDI-Datei zurück.
- `/interpretation/wav` Gleich wie der obige Endpunkt, allerdings wird vorher noch das MIDI mittels des MIDI-Synthesizers fluidsynth [23] in eine WAV-Datei konvertiert, so dass man die Interpretation direkt anhören kann.
- Außerdem liefert der Server die statischen Dateien der Webapplikation, wie das nötige HTML, JavaScript und CSS.

Die erwähnten Parameter sind nur folgende drei:

- Der Anfangsknoten der Interpretation im Graphen, den der Algorithmus benötigt (wie oben besprochen).
- Die Länge der Interpretation als die maximale Anzahl an Noten in der Interpretation.
- Der Startwert für den Pseudozufallszahlengenerator [14], der für die Interpretation verwendet werden soll. Da derselbe Startwert in die selbe Interpretation resultiert, erlaubt dies, sich interessante Interpretationen zu merken und zum Beispiel zu einer Interpretation noch die MIDI-Version zusätzlich herunterzuladen.

Dies ist auch schon alles, was das Serverbackend tut, denn es ist nur als minimaler Aufsatz auf die Library konzipiert. Das meiste für Benutzer*innen relevante passiert in der Webapplikation, die folgendermaßen aussieht:

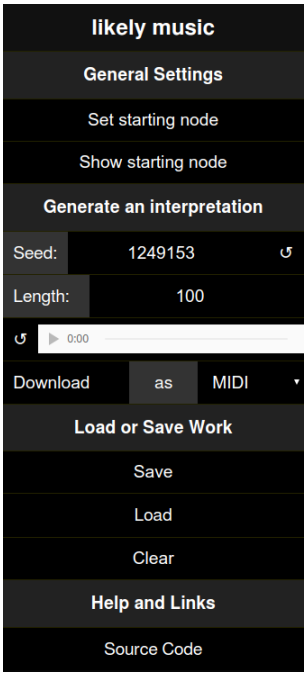


Den Kern der Applikation bildet der Grapheditor links, der auf der Library vis.js[2] [24] basiert. vis.js kümmert sich um einen sehr gut anpassbaren Grapheneditoren, in dem der*die Benutzer*in Knoten und Kanten hinzufügen, löschen und ändern kann. Da die Library Callbacks [26] bereitstellt, ist es leicht den Rest der Applikation mit dem Editor zu integrieren.

[2]Eigentlich nur ein Teil von vis.js namens *network* [25], aber ich werde vis.js immer der Kürze halber synonym für *vis.js network* verwenden.

Wenn ein Knoten oder eine Kante geändert wird, wird diese Änderung in eine Zustandsvariable der Applikation mitübernommen und die Zusatzinformationen der Knoten und Kanten, also Notenlänge und Tonhöhe (Knoten) bzw. Wahrscheinlichkeit (Kante), von dem*der Benutzer*in in einer Einblendung abgefragt und ebenfalls abgespeichert. So gelingt es, den Grapheditor so zu integrieren, dass der Graph zur Kommunikation mit dem Server und sonstiger Verarbeitung zur Verfügung steht. Die doppelte Speicherung der reinen Graphdaten kommt daher, dass vis.js es leider nicht erlaubt, die bereits im Editor vorhandenen Daten abzufragen, daher büßt die Architektur der Applikation leider ein wenig an Eleganz ein.

In der Seitenspalte passiert dann alles, was relevant für die Verarbeitung der links entstehenden Notation ist. Zum einen kann der Notationsgraph abgespeichert oder ein gespeicherter geöffnet werden, zum anderen ist es möglich, Interpretationen generieren zu lassen, diese direkt im Browser abzuspielen oder als MIDI oder WAV herunterzuladen. Die Seitenspalte ist im folgenden abgebildet.



Das Speichern und Öffnen von Notationen basiert auf JSON-Dateien [20] in bestimmten Format, die als `<dateiname>.score.json` abgespeichert werden. Eine solche enthält eine Liste aller Knoten plus Zusatzinformationen und eine Liste aller Kanten plus Zusatzinformationen. Wie eine solche aussehen kann, sieht man im Abschnitt Web (letzte Datei). Genau dieses Format wird übrigens auch zur Kommunikation mit dem Server verwendet, da es den Graphen verlustlos beschreiben kann.

Der Rest der Applikation kümmert sich vor allem um Interpretation und Export dieser. Oben in der Seitenleiste kann man die drei erwähnten Parameter setzen. Der Startknoten wird über markieren dessen im Editor und klicken des entsprechenden Buttons gesetzt und kann durch Hervorhebung im Graphen auch angezeigt werden. Der Startwert kann manuell eingegeben (etwa, wenn man sich einen besonderen notiert hat) oder ein zufälliger durch Verwendung des Buttons neben dem Feld verwendet werden. Die maximale Interpretationslänge ist dann darunter und wird ganz unspektakulär eingegeben.

Darunter befindet sich ein Audioplayer, mit dem erstellte Interpretationen direkt im Browser angehört werden können. Wenn man den Aktualisierungsbutton links betätigt, nimmt die Applikation alle Parameter sowie den aktuellen Graphen und sendet mithilfe der JavaScript Fetch API [27] den Graphen mitsamt der Parameter an den bereits erwähnten Endpunkt `/interpretation/wav`. Nach diesem Vorgang, der merklich Zeit benötigt, da fluidsynth [23] erst das WAV generieren muss, wird die Audiodatei in den Player geladen und kann direkt angehört werden.

Gleich unter dem Player kann man die Interpretation als MIDI oder WAV herunterladen. Dazu wählt man rechts eines der beiden Formate aus und klickt links auf „Download“. Intern funktioniert dies genau gleich wie der Player, bloß dass die jeweils der Endpunkte für das entsprechende Format verwendet wird und die Datei dann direkt heruntergeladen wird statt im Browser weiterverwendet wird.

Lizenzierung

Der gesamte Quelltext von *likely music* ist unter der *GNU Affero General Public License Version 3* lizenziert. Die AGPL ist eine Freie-Software-Lizenz [29], das heißt, sie sichert dem*der Benutzer*in gegenüber dem Entwickler verschiedene Rechte (typischerweise nennt man vier) zu. Diese Rechte haben alle emanzipatorischen Charakter für den Nutzer: Das Recht die Software so auszuführen, wie der Nutzer es mag, natürlich offensichtlichlerweise. Das Recht, den Quellcode zu erhalten und zu untersuchen hilft vor allem dem*der Benutzer*in zu verstehen, was eigentlich auf seinem*ihrem Com-

puter vor sich geht, und kann auch der Weiterbildung dienen. Die Freiheit, die Software frei und ohne Lizenzgebühren an andere weiterzugeben, ist mir besonders wichtig. Aufgrund diesen Umstandes kann freie Software unentgeltlich an jede*n weitergegeben werden, was Zugang zu Software unabhängig des eigenen Geldbeutels erlaubt – vorausgesetzt man besitzt einen Computer. Diese Freiheit geht sogar noch weiter, dahingehend, dass auch die Modifikation ausdrücklich erlaubt (und erwünscht) ist. Somit kann nicht nur jede*r freie Software erhalten, sondern auch mitgestalten und verbessern. Auch andere freie Software kann profitieren, indem sie von anderen Projekten Code übernimmt. Dank der restriktiven Weitergabeklauseln kann aber nie freie Software verwendet oder verändert werden, ohne dass sie wieder freie Software wird. Freie Software erhält sozusagen ihre eigene Freiheit.

Mir ist dies an dieser Stelle ein besonderes Anliegen, weil ich – mit Sicherheit im Gegensatz zu den allermeisten anderen Wettbewerbteilnehmer*innen – mein Projekt komplett mit freier Software erstellen konnte. Ich war nicht auf eine von drei teuren Softwarelösungen großer Konzerne angewiesen, um meinen Beitrag anzufertigen, wie das zum Beispiel im Bereich Videoschnitt der Fall ist (auch weil es kaum ausgereifte freie Software in dem Bereich gibt).

Insofern sehe ich auch den emanzipatorischen Charakter von freier Software, denn Zugang zu Computern ist größtenteils auch dank von Bibliotheken selbstverständlich geworden, Zugang zu Software, die mehrere hundert Euro kostet, aber mit Sicherheit nicht. Der Preis von Software, die ein Konzern vielleicht auch irgendwann verwahrlosen lässt, ist sicher für viele eine Hürde, vielleicht sogar eine Hürde an diesem Wettbewerb teilzunehmen.

Zukünftige Weiterentwicklung

likely music als fertig zu bezeichnen wäre nicht ganz falsch und nicht ganz richtig. Es handelt sich zwar um eine voll funktionsfähige Software, aber dennoch ist noch einige Weiterentwicklung, für die ich keine Zeit mehr hatte, denkbar. Folgende Gedanken hatte ich bisher:

- **Unterstützung für Akkorde im Interface.** Zwar unterstützen Euterpea und die Library beide Akkorde, aber im Frontend gibt es keine Möglichkeit, solche hinzuzufügen, da ich die Euterpea-MIDI-Datenstruktur nicht vollständig in JavaScript nachgebaut habe. Dies zu beheben wäre für die Zukunft auf jeden Fall wünschenswert.
- **Mehrstimmige bzw. parallele probabilistische Musik.** Denkbar wäre es, eine Möglichkeit hinzuzufügen mehrere Startknoten auszuwählen, von denen dann zwei gleichzeitige Pfade durch den Graph ausgingen. Dies scheint mir die interessantes Möglichkeit zu sein, Mehrstimmig für *likely music* umzusetzen.
- **Import bereits durchkomponierter Musik.** Indem man die Möglichkeit schafft, bereits in konventionellen Notationsprogrammen erstellte Musik zu importieren, könnte man ein für den*die Benutzer*in angenehme Möglichkeit bieten, konventionell notierter Musik ein probabilistisches Element zu geben bzw. sie probabilistisch umzusetzen.

Diese Änderungen stehen nicht im Konflikt mit dem bisherigen Grundkonzept und -aufbau von *likely music*, dürften daher ohne größere Probleme umgesetzt werden können.

Links

- Der gesamte Quelltext `https://github.com/sternenseemann/likely-music`
- Eine laufende Instanz[3] von *likely music* `https://likely.sternen.space`

Danksagung

- Meinem Lehrer Bastian Walcher für seine Betreuung meines Projekt und derer meiner Mitschüler*innen.

[3] *likely music* ist bisher noch nicht auf Performance optimiert worden. Ich glaube nicht, dass genannte Server einen größeren Ansturm vor allem wegen des Exports zu WAV (fluidsynth [23] ist ziemlich langsam) aushalten würde. Daher möchte ich darum bitten, diesen Link nicht zu veröffentlichen, sondern, falls etwas in der Art gewünscht sein sollte, mit mir Rücksprache zu halten.

- Lukas G. für sein Korrekturlesen.
- Christine S. für ihr Korrekturlesen.
- kohlrabi dafür, dass er sich mit mir über Musikprogrammierung und -theorie unterhielt und Ideen zu meinem Projekt beisteuerte.
- all dafür, dass er mich in Richtung Musikprogrammierung stieß.

Literatur

[1] https://de.wikipedia.org/wiki/Demoszene

[2] http://www.haskellforall.com/2012/07/purify-code-using-free-monads.html

[3] http://www.jackaudio.org/

[4] https://www.libsdl.org/index.php

[5] https://de.wikipedia.org/wiki/RIFF_WAVE

[6] https://www.midi.org/

[7] https://de.wikipedia.org/wiki/Musical_Instrument_Digital_Interface

[8] https://hackage.haskell.org/package/Euterpea

[9] https://github.com/sternenseemann/Euterpea2

[10] https://github.com/Euterpea/Euterpea2/issues/16

[11] https://hackage.haskell.org/package/containers-0.5.10.2/docs/Data-Map-Lazy.html#t:Map

[12] https://hackage.haskell.org/package/containers-0.5.10.2/docs/Data-Map-Lazy.html#v:lookup

[13] https://hackage.haskell.org/package/random-1.1/docs/System-Random.html#t:RandomGen

[14] https://en.wikipedia.org/wiki/Pseudorandom_number_generator

[15] https://de.wikipedia.org/wiki/Rekursion

[16] https://de.wikipedia.org/wiki/Lazy_Evaluation

[17] https://en.wikipedia.org/wiki/Client%E2%80%93server_model

[18] https://hackage.haskell.org/package/servant

[19] https://de.wikipedia.org/wiki/Representational_State_Transfer

[20] http://json.org/

[21] https://www.qt.io/

[22] https://www.gtk.org/

[23] http://www.fluidsynth.org/

[24] http://visjs.org/

[25] visjs.org/docs/network/

[26] https://en.wikipedia.org/wiki/Callback_(computer_programming)

[27] https://developer.mozilla.org/en-US/docs/Web/API/Fetch_API

[28] https://www.gnu.org/licenses/agpl-3.0.html

[29] https://www.gnu.org/philosophy/free-sw.de.html

Anhang

Quelltext

Library

lib/Sound/Likely.hs

```
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17
18 {-# LANGUAGE OverloadedStrings #-}
19 {-# LANGUAGE FlexibleInstances #-}
20 module Sound.Likely
21   ( Probability
22   , ID
23   , Node (..)
24   , Edge (..)
25   , Graph (..)
26   , insertNode
27   , insertEdge
28   , interpretation
29   , takeNotes
30   , emptyMusic
31   , exampleGraph
32   ) where
33
34 import Control.Monad
35 import Data.Aeson
36 import Data.Aeson.Types (Parser ())
37 import Data.Maybe
38 import Data.Text (Text ())
39 import Euterpea
40 import System.Random
41 import qualified Data.Map as M
42 import qualified Data.Set as S
43
44 type Probability = Double
45 type ID = Text
46
47 data Node
48   = Node
49   { nId :: ID
50   , nMusic :: Music Pitch
51   } deriving (Show, Eq, Ord)
52
53 data Edge
54   = Edge
55   { eTo   :: Node
```

```
56    , eProb :: Probability
57    } deriving (Show, Eq, Ord)
58
59  newtype Graph = Graph { unGraph :: M.Map Node (S.Set Edge) }
60    deriving (Show, Eq, Ord)
61
62  insertNode :: Node -> Graph -> Graph
63  insertNode t = Graph . M.insertWith S.union t S.empty . unGraph
64
65  insertEdge :: Node -> Edge -> Graph -> Graph
66  insertEdge n e =
67    insertNode n . Graph . M.insertWith S.union n (S.singleton e) . unGraph
68
69  interpretation :: RandomGen g => g -> Graph -> Node -> Music Pitch
70  interpretation gen graph n = (nMusic n) :+:
71    recurse (fromMaybe S.empty (M.lookup n (unGraph graph)))
72    where (prob, gen') = randomR (0.0, 1.0) gen
73          recurse edges =
74            if S.null edges
75              then emptyMusic
76              else interpretation gen' graph
77                   . eTo . edgeForRoll prob $ edges
78
79  edgeForRoll :: Probability -> S.Set Edge -> Edge
80  edgeForRoll prob set =
81    let curr = S.elemAt 0 set
82      in if prob <= eProb curr
83           then curr
84           else edgeForRoll (prob - eProb curr) (S.delete curr set)
85
86  emptyMusic :: Music a
87  emptyMusic = Prim (Rest 0)
88
89  exampleGraph :: Graph
90  exampleGraph = Graph $ M.fromList
91    [ (Node "bla" (c 4 qn), S.fromList [ Edge (Node "blub" (d 4 qn)) 1 ] )
92    , (Node "blub" (d 4 qn), S.fromList [ ])
93    ]
94
95  -- | Take the first @n@ notes of a 'Music'
96  takeNotes :: Integer -> Music a -> Music a
97  takeNotes _ m@(Prim _) = m
98  takeNotes n (Modify c m) = Modify c $ takeNotes n m
99  takeNotes _ m@(_ :=: _) = m
100 takeNotes n (m1 :+: m2)
101   | n <  1    = emptyMusic
102   | n == 1    = m1
103   | otherwise = m1 :+: takeNotes (n - 1) m2
104
105 instance FromJSON Node where
106   parseJSON = withObject "Node" $ \v ->
107     Node <$> v .: "id" <*> (Prim <$> v .: "music")
108
109 lookupNode :: Text -> [Object] -> Parser Node
110 lookupNode id nodes = do
111   matches <- filterM (fmap (== id) . (.: "id")) nodes
112   case matches of
113     [node] -> parseJSON (Object node)
114     _ -> fail "Couldn't␣match␣node␣by␣id"
115
116 buildMap :: [Object] -> [Object] -> Graph -> Parser Graph
117 buildMap _ [] m = pure m
```

```
118 buildMap nodes (e:es) m = do
119   toId <- e .: "to"
120   fromId <- e .: "from"
121   edge <- Edge <$> lookupNode toId nodes <*> e .: "prob"
122   from <- lookupNode fromId nodes
123   buildMap nodes es $ insertEdge from edge m
124
125 instance FromJSON Graph where
126   parseJSON = withObject "Graph" $ \v -> do
127     edges <- v .: "edges"
128     nodes <- v .: "nodes"
129     buildMap nodes edges $ Graph mempty
130
131 instance FromJSON (Primitive Pitch) where
132   parseJSON = withObject "Primitive" $ \v -> do
133     -- TODO Ratio _Integer_ is easy DOSable
134     -- RAM consumption
135     duration <- v .: "dur"
136     octave <- v .: "octave"
137     pitchClass <- v .: "pitch"
138     case pitchClass of
139       "Rest" -> pure $ Rest duration
140       p -> pure $ Note duration (read pitchClass, octave)
```

Backend

backend/Api.hs

```
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17
18 {-# LANGUAGE OverloadedStrings #-}
19 {-# LANGUAGE FlexibleInstances #-}
20 {-# LANGUAGE DataKinds         #-}
21 {-# LANGUAGE TypeOperators     #-}
22 module Api where
23
24 import Data.Aeson
25 import Data.ByteString.Lazy (ByteString ())
26 import Data.Monoid ((<>))
27 import Data.Ratio
28 import Data.Text (Text ())
29 import GHC.Generics
30 import Servant.API
31 import Sound.Likely
32
33 type LikelyApi = "interpretation" :> Capture "format" OutputFormat
34                                   :> ReqBody '[JSON] GraphWithParams
35                                   :> Post '[OctetStream] ByteString
36                 :<|> "seed" :> Get '[JSON] Int
37                 :<|> Raw
38
39 data OutputFormat = Midi | Wav
40   deriving (Show, Eq, Ord)
41
42 instance FromHttpApiData OutputFormat where
43   parseUrlPiece "mid" = Right Midi
44   parseUrlPiece "wav" = Right Wav
45   parseUrlPiece x     = Left $ "Couldn't␣match␣" <> x <> "␣with␣{mid,␣wav}"
46
47 data GraphWithParams
48   = GraphWithParams
49   { gpParams :: Params
50   , gpGraph  :: Graph
51   } deriving (Show, Eq, Ord)
52
53 instance FromJSON GraphWithParams where
54   parseJSON = withObject "GraphWithParams" $ \v ->
55     GraphWithParams <$> v .: "params"
56                     <*> v .: "graph"
57
58 data Params
59   = Params
```

```
60    { pMaxHops      :: Int
61    , pStartingNode :: Node
62    , pSeed         :: Int
63    } deriving (Show, Eq, Ord)
64
65  instance FromJSON Params where
66    parseJSON = withObject "Params" $ \v ->
67      Params <$> v .: "maxhops"
68             <*> v .: "starting_node"
69             <*> v .: "seed"
```

backend/Main.hs

```
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16  --  along with likely music. If not, see <http://www.gnu.org/licenses/>.
17
18  {-# LANGUAGE OverloadedStrings #-}
19  module Main where
20
21  import Api
22
23  import Codec.Midi (buildMidi)
24  import Codec.ByteString.Builder
25  import Control.Monad.IO.Class
26  import Data.ByteString.Lazy (ByteString ())
27  import qualified Data.ByteString.Lazy as B
28  import Euterpea hiding (app)
29  import GHC.IO.Handle
30  import Network.Wai
31  import Network.Wai.Handler.Warp
32  import Servant
33  import Sound.Likely
34  import System.Directory
35  import System.Exit
36  import System.Environment
37  import System.FilePath.Posix
38  import System.IO
39  import System.Process
40  import System.Random
41
42  api :: Proxy LikelyApi
43  api = Proxy
44
45  midiString :: ToMusic1 a => Music a -> ByteString
46  midiString = toLazyByteString . buildMidi . toMidi . perform
47
48  server :: Server LikelyApi
```

```haskell
server = genInterpretation :<|> randomSeed :<|> serveDirectoryWebApp "web/dist"

randomSeed :: Handler Int
randomSeed = liftIO newStdGen >>= return . fst . random

genInterpretation :: OutputFormat -> GraphWithParams -> Handler ByteString
genInterpretation Midi g = do
  let params       = gpParams g
      maxHops      = fromIntegral . pMaxHops $ params
      randomGen    = mkStdGen $ pSeed params
      song         = interpretation randomGen (gpGraph g) (pStartingNode params)
  return . midiString $ takeNotes maxHops song
genInterpretation Wav g = genInterpretation Midi g >>= synthWav

synthWav :: ByteString -> Handler ByteString
synthWav midi = do
  inName <- tempFile "mid"
  liftIO $ B.writeFile inName midi
  outName <- tempFile "wav"
  (_, _, _, ph) <- liftIO $
    createProcess_ "fluidsynth"
      (proc "fluidsynth"
        [ "-a", "file"
        , "-F", outName
        , "-i"
--        , "/usr/share/soundfonts/FluidR3_GM.sf2"
        , "/nix/store/591834mz365ccwyj3ah2d66ncsqvp8w9-Fluid-3/share/soundfonts/FluidR3_GM2-2.
            sf2"
        , inName ])
        { std_in = CreatePipe }
  code <- liftIO $ waitForProcess ph
  case code of
    ExitFailure _ -> throwError err500 { errBody = "fluidsynth␣failed" }
    ExitSuccess -> do
      out <- liftIO $ B.readFile outName
      liftIO $ removePathForcibly outName
      return out

tempFile :: String -> Handler FilePath
tempFile ext = try 0
  where maxtries = 100
        try :: Integer -> Handler FilePath
        try n
          | n < maxtries = do
            progName <- liftIO $ getProgName
            let path = "/tmp" </> addExtension (makeValid progName ++ "-" ++ show n) ext
            exists <- liftIO $ doesFileExist path
            if exists
              then try (n + 1)
              else pure path
          | otherwise = throwError err500
app :: Application
app = serve api server

main :: IO ()
main = newStdGen >> run 8081 app
```

Web

web/source/index.html

```
<!--

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-->
<!doctype html>
<html>
    <head>
        <meta charset="utf-8">
        <meta http-equiv="x-ua-compatible" content="ie=edge" />
        <meta name="viewport" content="width=device-width, initial-scale=1" />
        <title>likely music</title>
        <link rel="stylesheet" type="text/css" href="custom.css">
        <link rel="stylesheet" type="text/css" href="vis.min.css">
        <script src="main.js"></script>
    </head>
    <body>
        <div id="network"></div>
        <div id="sidebar">
            <h1>likely music</h1>
            <h2>General Settings</h2>
            <button id="set-starting-node">Set starting node</button>
            <button id="show-starting-node">Show starting node</button>
            <h2>Generate an interpretation</h2>
            <div class="multi-inputs">
                <label for="seed">Seed:</label>
                <input type="number" id="seed">
                <button id="random-seed">&#8634;</button>
            </div>
            <div class="multi-inputs">
                <label for="hop-count">Length:</label>
                <input type="number" min="0" id="hop-count" placeholder="Max. note count">
            </div>
            <div id="player-container">
                <button id="reload-player">&#8634;</button>
                <audio id="player" controls></audio>
            </div>
            <div class="multi-inputs">
                <button id="download-audio">Download</button>
                <label for="format">
                    as
                </label>
                <select id="format">
                    <option value="mid">MIDI</option>
```

```
                    <option value="wav">WAV</option>
                </select>
            </div>
            <h2>Load or Save Work</h2>
            <button id="gen-score" class="save">Save</button>
            <label for="upload-score" class="custom-file">
                <input type="file" id="upload-score" >
                <span>Load</span>
            </label>
            <button id="clear-score" class="cancel">Clear</button>
            <h2>Help and Links</h2>
            <a href="https://github.com/sternenseemann/likely-music">Source Code</a>
        </div>
        <div id="edge-overlay" class="hidden␣dialog">
            <h2><span id="edge-operation"></span> edge</h2>
            <div class="multi-inputs">
                <label for="prob">Probability:</label>
                <input id="prob" type="number" min="0.0" max="100">
                <span>%</span>
            </div>
            <div class="multi-inputs">
                <button class="save" id="edge-save">Save</button>
                <button class="cancel" id="edge-cancel">Cancel</button>
            </div>
        </div>
        <div id="node-overlay" class="hidden␣dialog">
            <h2><span id="node-operation"></span> node</h2>
            <div class="multi-inputs">
                <label for="pitch">Pitch:</label>
                <select id="pitch"></select>
            </div>
            <div class="multi-inputs">
                <label for="octave">Octave:</label>
                <input id="octave" type="number" step="1">
            </div>
            <div class="multi-inputs">
                <label>Duration:</label>
                <input min="0" id="numerator" type="number" step="1">
                <span>/</span>
                <input min="0" id="denominator" type="number" step="1">
            </div>
            <div class="multi-inputs">
                <button class="save" id="node-save">Save</button>
                <button class="cancel" id="node-cancel">Cancel</button>
            </div>
        </div>
    </body>
</html>
```

web/source/custom.css

```
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*/

body {
    font-size:1em;
    font-family: sans-serif;
    margin: 0px;
    background-color: black;
}

#network {
    width: 79%;
    float:left;
    height: 100vh;
}

#sidebar {
    width: 20%;
    float:right;
    color: white;
    background-color: black;
    box-shadow: 0px 0px 20px #111;
    font-size: 1.2rem;
}

#sidebar > * {
    width: 100%;
    border-top: 1px solid #232200;
    color: white;
    padding-left: 0px;
    padding-right: 0px;
    margin: 0;
}

#sidebar button:hover, #sidebar input:hover,
#sidebar .custom-file:hover, #sidebar select:hover, #sidebar a:hover {
    background-color: #563d7c;
}

#sidebar button, #sidebar input, #sidebar .custom-file, #sidebar select, #sidebar a {
  background-color: #000;
}

#sidebar h1 {
    font-size: 1.5rem;
    padding-top: 0.75rem;
```

```
    padding-bottom: 0.75rem;
    text-align: center;
    background-color: #111;
}

#sidebar h2 {
    font-size: 1.2rem;
    padding-top: 0.9rem;
    padding-bottom: 0.9rem;
    text-align: center;
    background-color: #222;
}

#sidebar select {
  color: white;
  border: none;
  padding: 0.75rem;
  font-size: 1.2rem;
  width: auto;
}

#sidebar a {
  padding-bottom: 0.75rem;
  padding-top: 0.75rem;
  display: inline-block;
  text-decoration: none;
  color: white;
  text-align: center;
}

button {
    border: none;
    color: white;
    background-color:black;
    font-size: 1.2rem;
    margin:0;
    padding:0.75rem;
}

input[type="number"] {
    background-color: #333;
    color: white;
    border: none;
    text-align: center;
    font-size: 1.2rem;
    padding:0.75rem;
}

.custom-file {
    top:0;
    right:0;
    position: relative;
    display: inline-block;
    height: 3rem;
}

.custom-file input[type="file"] {
    position: relative;
    top:0;
    left:0;
    right:0;
    z-index:0;
```

```
    opacity: 0;
    width: 100%;
    height: 100% !important;
    margin:0;
    padding:0;
}

.custom-file span {
    text-align: center;
    position: absolute;
    top: 0;
    left: 0;
    right: 0;
    z-index: 1;
    width: 100%;
    height: 3rem;
    pointer-events: none;
    background-color: transparent !important;
    font-size: 1.2rem;
    line-height: 1.5rem;
    padding-top: 0.75rem;
    padding-bottom: 0.75rem;
}

.dialog {
    position: absolute;
    top: 10%;
    left: 25%;
    width: 30%;
    min-width:500px;
    padding: 10px;
    background-color: black;
    color: white;
    box-shadow: 0px 0px 10px #111;
}

.dialog > div {
    height: 3rem;
}

.hidden {
    visibility:hidden;
}

.dialog > div {
  width: 100%;
}

.dialog button {
    padding: 0.75rem;
    font-size: 1.5rem;
}

button.cancel {
    background-color: #a23a30;
}

button.save {
    background-color: #0ea92f;
}

.dialog .multi-inputs {
```

```
  font-size: 1.5rem;
}

.multi-inputs {
  display: inline-flex;
  flex-direction: row;
  flex-wrap: nowrap;
  justify-content: flex-start;
  align-items: baseline;
  width: 100%;
}

.multi-inputs > * {
  flex-grow: 1;
  flex-basis: auto;
  transition: width 0.7s ease-out;
  max-height: 100%;
  text-align: center;
}

.multi-inputs :nth-child(1) {
  text-align: left;
}

.multi-inputs label {
  display: inline-block;
  background-color: #333;
  padding: 0.75rem;
}

.multi-inputs input {
  display: inline-block;
  color: white;
  background-color: #111;
  padding: 0.75rem;
  border: none;
  min-width: 0px;
}

.multi-inputs span {
  display: inline-block;
  padding: 0.75rem;
  background-color: #222;
}

.multi-inputs button {
    padding: 0.75rem;
}

#player-container {
  display: inline-flex;
  align-items: center;
}

#player-container > * {
  flex: auto;
}
```

web/source/main.js

```
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import vis from 'vis';
import { Map } from 'immutable';
// types / internals

const valid_pitches = [
    'Rest',
    'Cff', 'Cf', 'C',
    'Dff', 'Cs', 'Df',
    'Css', 'D', 'Eff',
    'Ds', 'Ef', 'Fff',
    'Dss', 'E', 'Ff',
    'Es', 'F', 'Gff',
    'Ess', 'Fs', 'Gf',
    'Fss', 'G', 'Aff',
    'Gs', 'Af', 'Gss',
    'A', 'Bff', 'As',
    'Bf', 'Ass', 'B',
    'Bs', 'Bss'
];

const display_pitches = [
    'Rest',
    ' C', ' C', 'C',
    ' D', ' C', ' D',
    ' C', 'D', ' E',
    ' D', ' E', ' F',
    ' D', 'E', ' F',
    ' E', 'F', 'Gff',
    ' E', ' F', ' G',
    ' F', 'G', ' A',
    ' G', ' A', ' G',
    'A', ' B', ' A',
    ' B', ' A', 'B',
    ' B', ' B'
];

function displayPitch(pitch) {
    var i = valid_pitches.indexOf(pitch);
    if(i === -1) {
        throw 'Invalid pitch';
    } else {
        return display_pitches[i];
    }
}
```

```
62
63  function standard_rests(dur) {
64      if(dur.numerator === 1) {
65          switch(dur.denominator) {
66              case 1:
67                  return  ' ';
68                  break;
69              case 2:
70                  return  ' ';
71                  break;
72              case 4:
73                  return  ' ';
74                  break;
75              case 8:
76                  return  ' ';
77                  break;
78              case 16:
79                  return  ' ';
80                  break;
81              case 32:
82                  return  ' ';
83                  break;
84              case 64:
85                  return  ' '
86                  break;
87              case 128:
88                  return  ' '
89                  break;
90              default:
91                  return null;
92                  break;
93          }
94      } else {
95          return null;
96      }
97  }
98
99  function standard_notes(dur) {
100     if(dur.numerator === 1) {
101         switch(dur.denominator) {
102             case 1:
103                 return  ' ';
104                 break;
105             case 2:
106                 return  ' ';
107                 break;
108             case 4:
109                 return  ' ';
110                 break;
111             case 8:
112                 return  ' ';
113                 break;
114             case 16:
115                 return  ' ';
116                 break;
117             case 32:
118                 return  ' ';
119                 break;
120             case 64:
121                 return  ' '
122                 break;
123             case 128:
```

```
                return  ' '
                break;
            default:
                return null;
                break;
        }
    } else if(dur.numerator === 2 && dur.denominator === 1) {
        return  ' '
    } else {
        return null;
    }
}

function compute_dot_times(dur, den) {
    let term = den * ( (2 / den) - (dur.numerator / dur.denominator));
    return [ den, -Math.log2(term) ];
}

function musical_symbol(lookup, dur) {
    // unicode characters sometimes hide from you!
    const dot =  ' ';
    let isNat = n => {
        if (typeof n !== 'number')
            return false;
        return (n >= 0.0) && (Math.floor(n) === n) && n !== Infinity;
    };
    var standard_symbol = lookup(dur);
    var bla = [0, 1, 2, 3, 4, 5, 6, 7 ].map(compute_dot_times.bind(this, dur));
    console.log(bla);
    var dots = bla.filter(([den, dots]) => isNat(dots));
    console.log(dots);

    if(standard_symbol !== null) {
        return standard_symbol;
    } else if (dots.length !== 0) {
        var symbol = lookup(new Rational(1, dots[0][0])) + ' ';
        for(var i = dots[0][1]; i > 0; i--) {
            symbol = symbol + dot;
        }
        return symbol;
    } else {
        return dur.toString();
    }
}

class Music {
    constructor(dur, pitch_class, octave) {
        this.dur = dur;
        if(valid_pitches.indexOf(pitch_class) !== -1) {
            this.pitch = pitch_class;
        } else {
            throw `Invalid pitch class '${pitch_class}'`;
        }
        this.octave = octave;
    }

    toString() {
        if(this.pitch === 'Rest') {
            return `${displayPitch(this.pitch)} for ${this.dur.toString()}`;
        } else {
            return `${displayPitch(this.pitch)}${this.octave} for ${this.dur.toString()}`;
        }
```

```
186     }
187
188     nodeText() {
189         if(this.pitch === 'Rest') {
190             return `${musical_symbol(standard_rests, this.dur)} Rest`;
191         } else {
192             return `${musical_symbol(standard_notes, this.dur)}   ${displayPitch(this.pitch)}$
                {this.octave}`
193         }
194     }
195
196
197     static fromObject(obj) {
198         return new Music(Rational.fromObject(obj.dur), obj.pitch, Number(obj.octave));
199     }
200 }
201
202 class Rational {
203     constructor(a, b) {
204         this.numerator = a;
205         this.denominator = b;
206         this.reduce();
207     }
208
209     reduce() {
210         let gcd = (a, b) => !b ? a : gcd(b, a % b);
211         let div = function(a, b) {
212             if(b === 0) {
213                 throw 'Divide by zero';
214             } else {
215                 return Math.floor(a / b);
216             }
217         };
218
219         var d = gcd(this.numerator, this.denominator);
220         this.numerator = div(this.numerator, d);
221         this.denominator = div(this.denominator, d);
222     }
223
224     toString() {
225         return `${this.numerator}/${this.denominator}`;
226     }
227
228     static fromObject(obj) {
229         return new Rational(obj.numerator, obj.denominator);
230     }
231 }
232
233 function collectGraphData(nodeDate, edgeData) {
234     return {
235         nodes: [... nodeData.values()].map(x => ({
236             id: x.nodeData.id,
237             music: x.music
238         })),
239         edges: [... edgeData.values()].map(x => ({
240             id: x.edgeData.id,
241             from: x.edgeData.from,
242             to: x.edgeData.to,
243             prob: x.prob
244         }))
245     };
246 }
```

```
247
248 function importGraphData(g) {
249     nodeData = new Map();
250     edgeData = new Map();
251     var nodeSet = new vis.DataSet({});
252     var edgeSet = new vis.DataSet({});
253     for(let node of g.nodes) {
254         var music = Music.fromObject(node.music);
255         var data = { id: node.id, label: music.nodeText() };
256         nodeData = nodeData.set(node.id, { nodeData: data, music: node.music });
257         nodeSet.add(data);
258     }
259
260     for(let edge of g.edges) {
261         var data = {
262             id: edge.id,
263             from: edge.from,
264             to: edge.to,
265             label: `${edge.prob * 100}%`
266         };
267         edgeData = edgeData.set(edge.id, { edgeData: data, prob: edge.prob });
268         edgeSet.add(data);
269     }
270
271     network.setData({ nodes: nodeSet, edges: edgeSet });
272 }
273
274 // helper
275
276 function download(url, filename) {
277     var link = document.createElement('a');
278     link.setAttribute('href', url);
279     link.setAttribute('download', filename);
280     link.style.display = 'none';
281     document.body.appendChild(link);
282     link.click();
283     document.body.removeChild(link);
284 }
285
286 function downloadFile(content_type, filename, content) {
287     var data = `data:${content_type},${encodeURIComponent(content)}`;
288     download(data, filename);
289 }
290
291
292 // graph code
293
294 var nodeData = Map();
295 var edgeData = Map();
296 var network = null;
297 var starting_node_id = null;
298
299
300 function showOverlay(id) {
301     document.getElementById(id).classList.remove('hidden');
302 }
303
304 function genericEditNode(data, callback) {
305     function clearOverlay() {
306         document.getElementById('node-save').onclick = null;
307         document.getElementById('node-cancel').onclick = null;
308         hideOverlay('node-overlay');
```

```
309     }
310
311     function saveNode(data, callback) {
312         var duration = new Rational(document.getElementById('numerator').value,
313             document.getElementById('denominator').value);
314         var music = new Music(duration, document.getElementById('pitch').value,
315             Number(document.getElementById('octave').value));
316         data.label = music.nodeText();
317         clearOverlay();
318         callback(data);
319         nodeData = nodeData.set(data.id, { music: music, nodeData: data });
320     }
321
322     function discardNode(callback) {
323         clearOverlay();
324         callback(null);
325     }
326
327     showOverlay('node-overlay');
328     var node = nodeData.get(data.id);
329     if(node !== undefined) {
330         var music = node.music;
331         document.getElementById('pitch').value = music.pitch;
332         document.getElementById('octave').value = music.octave;
333         document.getElementById('numerator').value = music.dur.numerator;
334         document.getElementById('denominator').value = music.dur.denominator;
335     }
336     document.getElementById('node-save').onclick = saveNode.bind(this, data, callback);
337     document.getElementById('node-cancel').onclick = discardNode.bind(this, callback);
338 }
339
340 function genericEditEdge(data, callback) {
341     function clearOverlay() {
342         document.getElementById('edge-save').onclick = saveEdge.bind(this, data, callback);
343         document.getElementById('edge-cancel').onclick = discardEdge.bind(this, callback);
344         hideOverlay('edge-overlay');
345     }
346
347     function saveEdge(data, callback) {
348         // for some reason, editWithoutDrag
349         // sets from & to to the node respective
350         // node objects, which results in the edge
351         // disappearing.
352         if (typeof data.to === 'object')
353             data.to = data.to.id
354         if (typeof data.from === 'object')
355             data.from = data.from.id
356
357         var prob = document.getElementById('prob').value / 100;
358         data.label = `${prob * 100}%`;
359         clearOverlay();
360         callback(data);
361         edgeData = edgeData.set(data.id, { prob: prob, edgeData: data } );
362     }
363
364     function discardEdge(callback) {
365         clearOverlay();
366         callback(null);
367     }
368
369     showOverlay('edge-overlay');
370     var edge = edgeData.get(data.id);
```

```
371     if(edge !== undefined) {
372         document.getElementById('prob').value = edge.prob * 100;
373     }
374     document.getElementById('edge-save').onclick = saveEdge.bind(this, data, callback);
375     document.getElementById('edge-cancel').onclick = discardEdge.bind(this, callback);
376 }
377
378 function deleteFromMap(data, callback) {
379     for(let node of data.nodes) {
380         nodeData = nodeData.delete(node);
381     }
382
383     for(let edge of data.edges) {
384         edgeData = edgeData.delete(edge);
385     }
386
387     callback(data);
388 }
389
390
391 function hideOverlay(id) {
392     document.getElementById(id).classList.add('hidden');
393 }
394
395 function handleImport() {
396     var files = document.getElementById('upload-score').files;
397     if(files.length === 0) {
398         alert('Select a file first!');
399     } else {
400         var file = files[0];
401         var reader = new FileReader();
402         reader.addEventListener('loadend', function() {
403             var parsed = JSON.parse(this.result);
404             if(parsed === undefined) {
405                 alert('Could not parse likely score');
406             } else {
407                 var confirmation = window.confirm('Proceeding will overwrite the current graph
                        . Are you sure?');
408                 if(confirmation) {
409                     try {
410                         importGraphData(parsed);
411                     } catch(e) {
412                         alert(`Could not import likely score, probably the file was malformed.
                                Error: ${e}`);
413                     }
414                 }
415             }
416         });
417         reader.readAsText(file);
418     }
419 }
420
421 function saveDataToLocalStorage() {
422     const json = JSON.stringify(collectGraphData(nodeData, edgeData));
423     const params = JSON.stringify(gatherParams());
424     localStorage.setItem("score", json)
425     localStorage.setItem("params", params)
426 }
427
428 function showStartingNode() {
429     if(typeof starting_node_id === 'string') {
430         network.selectNodes([starting_node_id], false);
```

```
    } else {
        alert('No starting node selected yet!');
    }
}

function setStartingNode() {
    var selected = network.getSelectedNodes();
    if(selected.length > 1) {
        alert('Only select one node!');
    } else if(selected.length === 0) {
        alert('Select a node first!');
    } else {
        starting_node_id = selected[0];
    }
}

function fetchInterpretation(params, format) {
    var jsonRequest = JSON.stringify({
        graph: collectGraphData(nodeData, edgeData),
        params: params
    });

    var myHeaders = new Headers();
    myHeaders.set('Content-Type', 'application/json');

    var myInit = {
        method: 'POST',
        headers: myHeaders,
        mode: 'cors',
        body: jsonRequest
    };

    var myRequest = new Request(`/interpretation/${format}`, myInit);

    return fetch(myRequest).then(res => res.blob());
}

function gatherParams() {
    var starting_node_entry = nodeData.get(starting_node_id);
    if(starting_node_entry !== undefined && starting_node_entry !== null) {
        var starting_node = {
            id: starting_node_entry.nodeData.id,
            music: starting_node_entry.music
        };
    } else {
        var starting_node = null
    }

    var maxhops = document.getElementById('hop-count').value;
    if(maxhops === "" || Number(maxhops) === NaN) {
        maxhops = null;
    } else {
        maxhops = Number(maxhops);
    }

    var seed = document.getElementById('seed').value;
    if(seed === "" || Number(seed) === NaN) {
        seed = null;
    } else {
        seed = Number(seed);
    }

```

```
493     return {
494         maxhops:  maxhops,
495         starting_node: starting_node,
496         seed: seed
497     };
498 }
499 
500 function completeGatherParams() {
501     var p = gatherParams();
502     if(p.starting_node === null) {
503         alert('Set a starting node first!');
504         return null;
505     }
506 
507     if(p.maxhops === null) {
508         alert('Set the maximum amount of hops to a valid number');
509         return null;
510     }
511 
512     if(p.seed === null) {
513         // TODO auto generate a random one, let the user confirm before
514         alert('Set the seed to a valid number!');
515         return null;
516     }
517 
518     return p;
519 }
520 
521 function importParams(p) {
522     if(p.starting_node !== null) {
523         starting_node_id = p.starting_node.id;
524     }
525     if(p.seed !== null) {
526         document.getElementById('seed').value = p.seed;
527     }
528     if(p.maxhops !== null) {
529         document.getElementById('hop-count').value = p.maxhops;
530     }
531 }
532 
533 function randomSeed() {
534     if(window.crypto) {
535         var array = new Int32Array(1);
536         window.crypto.getRandomValues(array);
537         document.getElementById('seed').value = array[0];
538     }
539 }
540 
541 function downloadInterpretation(format) {
542     var params = completeGatherParams();
543     if(params != null) {
544         try {
545             fetchInterpretation(params, format).then(file => {
546                 var url = URL.createObjectURL(file);
547                 download(url, `export.${format}`);
548                 URL.revokeObjectURL(url);
549             });
550         } catch(e) {
551             alert('An error occured while contacting the API: ' + e);
552         }
553     }
554 }
```

```
555
556 function reloadPlayer() {
557     var params = completeGatherParams();
558     if(params !== null) {
559         if(document.getElementById('player').src) {
560             URL.revokeObjectURL(document.getElementById('player').src);
561         }
562
563         document.getElementById('player').src = null;
564
565         try {
566             fetchInterpretation(params, 'wav').then(file => {
567                 var url = URL.createObjectURL(file);
568                 document.getElementById('player').src = url;
569             });
570         } catch(e) {
571             alert('An error occured while contacting the API: ' + e);
572         }
573     }
574 }
575
576 function init() {
577     var container = document.getElementById('network');
578
579     var options = {
580         manipulation: {
581             addNode: function(nodeData, callback) {
582                 document.getElementById('node-operation').innerHTML = 'Add';
583                 genericEditNode(nodeData, callback);
584             },
585             addEdge: function(edgeData, callback) {
586                 document.getElementById('edge-operation').innerHTML = 'Add';
587                 genericEditEdge(edgeData, callback);
588             },
589             editNode: function(nodeData, callback) {
590                 document.getElementById('node-operation').innerHTML = 'Edit';
591                 genericEditNode(nodeData, callback);
592             },
593             editEdge: {
594                 editWithoutDrag: function(edgeData, callback) {
595                     document.getElementById('edge-operation').innerHTML = 'Edit';
596                     genericEditEdge(edgeData, callback);
597                 }
598             },
599             deleteNode: deleteFromMap,
600             deleteEdge: deleteFromMap,
601             controlNodeStyle: {
602             }
603         },
604         nodes: {
605             borderWidth: 0,
606             color: {
607                 background: '#563d7c',
608                 hover: {
609                     background: '#8f14ff'
610                 },
611                 highlight: {
612                     background: '#8f14ff'
613                 }
614             },
615             chosen: true,
616             font: {
```

```
                color: 'white',
                size: 20,
                align: 'center'
            },
            shape: 'circle',
        },
        edges: {
            arrows: {
                to: { enabled: true }
            },
            color: {
                color: '#563d7c',
                hover: '#563d7c',
                highlight: '#563d7c',
            },
            font: {
                color: '#ffffff',
                strokeWidth: 0
            }
        }
    };

    network = new vis.Network(container, {}, options);

    try {
        const score = localStorage.getItem('score');
        if(score !== null) {
            importGraphData(JSON.parse(score));
        }
    } catch(e) {
        localStorage.removeItem('score');
    }

    try {
        const params = localStorage.getItem('params')
        if(params !== null) {
            importParams(JSON.parse(params));
        }
    } catch(e) {
        localStorage.removeItem('params');
    }

    const pitch_selector = valid_pitches.map((p, i) =>
        `<option value="${p}">${display_pitches[i]}</option>`)
        .reduce((acc, v) =>
            acc + v, '');
    document.getElementById('pitch').innerHTML = pitch_selector;

    /* event handling, order as in sidebar */
    document.getElementById('set-starting-node').onclick = setStartingNode;
    document.getElementById('show-starting-node').onclick = showStartingNode;

    document.getElementById('random-seed').onclick = randomSeed;

    document.getElementById('reload-player').onclick = reloadPlayer;
    document.getElementById('download-audio').onclick = () => {
        var format = document.getElementById('format').value;
        downloadInterpretation(format);
    };

    document.getElementById('gen-score').onclick = () =>
        downloadFile('application/json', 'score.likely.json',
```

```
679             JSON.stringify(collectGraphData(nodeData, edgeData)));
680     document.getElementById('upload-score').addEventListener('change',handleImport);
681     document.getElementById('clear-score').onclick = () =>
682         importGraphData({ nodes: [], edges: []});
683 
684     window.setInterval(saveDataToLocalStorage, 5000);
685 }
686 
687 document.addEventListener('DOMContentLoaded', () => init());
```

Graph im JSON Format der Webapplikation


```
{
  "nodes": [
    {
      "id": "d3c408d5-1ebb-4787-b510-22af5fe7093a",
      "music": {
        "dur": {
          "numerator": 3,
          "denominator": 4
        },
        "pitch": "Cf",
        "octave": 1
      }
    },
    {
      "id": "180159e7-527b-4b8a-b9b6-315dddc154d2",
      "music": {
        "dur": {
          "numerator": 2,
          "denominator": 4
        },
        "pitch": "C",
        "octave": 1
      }
    },
    {
      "id": "02e24c99-780e-45da-bd2f-ea600e4d863f",
      "music": {
        "dur": {
          "numerator": 1,
          "denominator": 1
        },
        "pitch": "Rest",
        "octave": 1
      }
    },
    {
      "id": "b9cd3f9d-134c-4c51-b325-d209b2529bd6",
      "music": {
        "dur": {
          "numerator": 1,
          "denominator": 8
        },
        "pitch": "F",
        "octave": 1
      }
    }
  ],
  "edges": [
    {
      "id": "f8d0cb23-00d1-49dd-961a-2114b8a89c1d",
      "from": "d3c408d5-1ebb-4787-b510-22af5fe7093a",
      "to": "180159e7-527b-4b8a-b9b6-315dddc154d2",
      "prob": 1
    },
    {
      "id": "283100d9-42ee-4001-b100-45b8c766cfc5",
      "from": "b9cd3f9d-134c-4c51-b325-d209b2529bd6",
      "to": "02e24c99-780e-45da-bd2f-ea600e4d863f",
      "prob": 0.8
    },
    {
```

```
      "id": "e6cceb76-40ed-49ac-8925-4534cf0854de",
      "from": "02e24c99-780e-45da-bd2f-ea600e4d863f",
      "to": "d3c408d5-1ebb-4787-b510-22af5fe7093a",
      "prob": 0.2
    },
    {
      "id": "0045bfda-3cde-4691-81c0-7a967be51e02",
      "from": "02e24c99-780e-45da-bd2f-ea600e4d863f",
      "to": "180159e7-527b-4b8a-b9b6-315dddc154d2",
      "prob": 0.8
    },
    {
      "id": "ec616a31-7fc0-4f27-ae31-79cf0fab224a",
      "from": "b9cd3f9d-134c-4c51-b325-d209b2529bd6",
      "to": "180159e7-527b-4b8a-b9b6-315dddc154d2",
      "prob": 0.2
    },
    {
      "id": "14735fda-b8e5-4567-aa1c-de04cc08ac24",
      "from": "180159e7-527b-4b8a-b9b6-315dddc154d2",
      "to": "b9cd3f9d-134c-4c51-b325-d209b2529bd6",
      "prob": 1
    }
  ]
}
```

Lizenz

Preamble

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The precise terms and conditions for copying, distribution and modification follow.

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