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Generation of sequences controlled by their “complexity”

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Abstract

We want to generate sequences of musical “chords” (a chord is a set of notes basically) with some known constraints (allDiff, etc.) as well as control on the complexity of the sequence. This complexity in turn is defined by a dynamic programming algorithm working on the instantiated sequence, which makes the whole problem difficult.

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1 Problem description

2 Definitions and notations

In this section we fix some notations that will be reused next.

$G = (V, A)$ is a directed graph where $V = (v_1, \dots, v_n)$ is the set of its vertices and $A = (a_1, \dots, a_m)$ is the set of its arcs. n and m represents the cardinality of respectively V and A . An arc $a_i \in A$ is a pair $(v_i, v_j) \in V^2$ saying that a_i goes from v_i to v_j . The arc (v_i, v_j) is different from (v_j, v_i) .

colF is the coloring function and takes an arc a as parameters. It returns the set of colors \mathbb{C} associated to a . By abuse of notation we say that $\text{colF}(a) = \text{colF}(v_i, v_j)$ if $a = (v_i, v_j)$.

$R : A \rightarrow \mathbb{N}$ is the affectation function, and $R(e) = c$ if $c \in \text{colF}(e)$. For simplicity, if $P = (a_1, \dots, a_k)$ is a list of consecutive arcs whose length is k , then $\text{colF}(P) = (\text{colF}(a_1), \dots, \text{colF}(a_k)) = (\mathbb{C}_1, \dots, \mathbb{C}_k)$ and $R(P) = (R(a_1), \dots, R(a_k)) = (c_1, \dots, c_k)$.

Given a path P of length k and its corresponding affectations $H = R(P)$, the weight of H is the number of its color switches. This cost is computed by $w(R(P))$.

$$w(H) = \sum_{i=1}^{k-1} (c_i \neq c_{i+1}) \quad (1)$$

$w_{OPT}(H)$ is the minimal weight of a path among all the possible affectation H of P , H_{OPT} is an optimal affectation.

Finally, we say that a shortest path from v_i to v_j in a graph G is a path P starting in v_i and ending in v_j whose optimal affectation H_{OPT} is the minimal among all the other possible paths in G .

3 Minimize Switches in Paths

The goal of this section is to provide a greedy algorithm able to compute an optimal affectation H of a given path P . The obtained result, will then be extended to general graphs using the matrix technique proposed in [Section 4.3](#) or the MDD strategy of [Section 5.2](#).

3.1 Procedure

This problem can be solved through a greedy strategy: taking a path P and a coloring function colF , we delay a color switch as much as possible. The algorithm is decomposed in two main parts where the first affects each arc a_i to a subset of colors of $\text{colF}(a_i)$ and where the second makes a unique affectation for each arc.

Procedure part 1. In this part of the procedure, we affect each arc of a path (a_1, \dots, a_k) to a subset of colors $(\mathbb{C}_1, \dots, \mathbb{C}_k)$. The colors associated to a_1 , noted \mathbb{C}_1 , are exactly $\text{colF}(a_1)$. Next, the set of colors \mathbb{C}_i of the arc a_i ($i > 1$) will be iteratively given by the intersection of \mathbb{C}_{i-1} and $\text{colF}(a_i)$ if the intersection is non-empty, otherwise, a color switch is imminent and, therefore, \mathbb{C}_i will be $\text{colF}(a_i)$.

Procedure part 2. In this second part of the procedure, we make a unique color affectation from the list $\mathcal{L} = (\mathbb{C}_1, \dots, \mathbb{C}_k)$ returned by the previous procedure. We read the \mathcal{L} from right to left. The color c_k affected to the last arc of P is a color randomly chosen from \mathbb{C}_k . The color of i^{th} arc a_i ($i < k$) is the color c_{i+1} affected to the arc a_{i+1} , if c_{i+1} is in \mathbb{C}_i , otherwise, we are facing a color switch, and, therefore, any color of \mathbb{C}_i can be indifferently affected to a_i .

An implementation of this procedure can be found in [Algorithm 2](#).

Proof (First part of the procedure). Let $H_{\mathbb{C}} = (\mathbb{C}_1, \dots, \mathbb{C}_k)$ be a solution returned by the first part of our algorithm, we prove, by induction on the length of the path, that $H_{\mathbb{C}}$ minimizes the number of color switches. After this first proof, we will show that the number of color switches returned by the second part of the algorithm is the same as the one returned by the first part.

By definition of the weight function, if the length k of the path is 1 we have $w(H_{\mathbb{C}}) = 0$ which is the optimal cost. And therefore, any color chosen from \mathbb{C}_1 will not cause any color switch.

Let's suppose that $H_{\mathbb{C}}$ is an optimal solution for every path of length at least k . We want to prove that arc new affectation $H'_{\mathbb{C}}$ returned by the algorithm for a path of length $k + 1$ is still optimal.

We have to analyze two main situations:

- if $\text{colF}(a_k) \cap \text{colF}(a_{k+1}) = \emptyset$ then, for any color c chosen from $\text{colF}(a_{k+1})$, $w(H'_C) = w(H_C) + 1$, *i.e.* a color switch is forced independently on the affectation we have chosen for the first part of the list. Since, by hypothesis, H_C is optimal, $w(H')$ remains optimal.
- otherwise, if $\text{colF}(a_k) \cap \text{colF}(a_{k+1}) \neq \emptyset$ we have two sub-cases to treat:
 - if it exists a subset of colors $\mathbb{C}_{k+1} \subseteq \text{colF}(a_{k+1})$ which is included in \mathbb{C}_k , *i.e.* there exists at least a color in $\text{colF}(a_{k+1})$, we are able to avoid a color switch. therefore, the cost of the affectation H'_C of the new path of length $k + 1$ equals $w(H_C)$. Again, since the affectation H_C is optimal, and we do not increase the number of color switches then the new affectation H'_C is still optimal.
 - this final case is the most interesting to treat because the intersection between \mathbb{C}_k and $\text{colF}(a_{k+1})$ is empty, but, on the other hand, $\text{colF}(a_k) \cap \text{colF}(a_{k+1}) \neq \emptyset$. It means that the particular choice of colors associated to the arc a_k is causing a color switch, even if it had been possible to make no color break between the k^{th} arc and the $(k + 1)^{\text{th}}$ arc of P . The cost of the affectation H'_C is therefore, $w(H_C) + 1$.
Let's suppose, by means of contradiction, that it exists a better affectation H_{Copt} of subsets for (a_1, \dots, a_{k+1}) . Without loss of generality, let's suppose that the intersection of the colors of the first k arcs of the path is not empty, *i.e.* there exists at least one color shared by all the a_i ($0 \leq i \leq k$) first arcs. The cost of this subpath is 0 since all of the arcs can have the same color. If we want to add the new arc a_{k+1} to the path, without increasing the number of color switches, it must exist at least one color belonging to $\bigcap_{i=1}^k \text{colF}(i)$. However, this condition is not possible, otherwise the algorithm would have kept this subset of color as a valid option for every arc of the path. A contradiction.

We can conclude that the number of color switches returned by the first part of the procedure is minimal, therefore, optimal. \square

Proof (Second part of the procedure). In the previous proof, we have shown that the number of color switches return by the first part of the algorithm is minimal. We only have to prove that its second part return an affectation with the same number of colors switches.

Let $(\mathbb{C}_1, \dots, \mathbb{C}_k)$ be the subset affectation returned by the previous part of the algorithm. Note that, by construction of the first algorithm, for each set \mathbb{C}_i , its successor \mathbb{C}_{i+1} is either a subset of \mathbb{C}_i or $\mathbb{C}_i \cap \mathbb{C}_{i+1} = \emptyset$. Starting from the last arc of the path, we can choose an arbitrary color $c_k \in \mathbb{C}_k$ for the arc a_k . Then for the arc a_{k-1} , we choose the same color of a_k if possible and repeat the same procedure until reaching the first arc of the path.

We have, therefore, a color switch only when the intersection of \mathbb{C}_i and \mathbb{C}_{i+1} is empty. \square

3.2 Time Complexity

We can analyze the time complexity of this procedure from the implementation proposed in [Algorithm 2](#). We have two loops of size k (the length of the path). Inside them we make intersection between sets of at most s colors, then the intersection between two sets of that size will take $\mathcal{O}(s)$. Finally, the global time complexity will be $\mathcal{O}(2 * k * s) = \mathcal{O}(k * s)$.

3.3 An example run

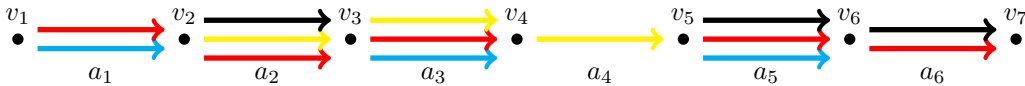


Figure 1: A path example

Let's take [Figure 1](#), where $P = (a_1, \dots, a_6)$ and colF such that

$$\begin{aligned} \text{colF}(P) = (&\{\text{cyan}, \text{red}\}, \{\text{red}, \text{yellow}, \text{black}\}, \\ &\{\text{cyan}, \text{red}, \text{yellow}\}, \{\text{yellow}\}, \\ &\{\text{cyan}, \text{red}, \text{black}\}, \{\text{red}, \text{black}\}) \end{aligned}$$

Here we give a solution of how the procedure proposed in [Section 3.1](#) would solve it. The first procedure will return a list of subsets equal to

$$H_{\mathbb{C}} = (\{cyan, red\}, \{red\}, \\ \{red\}, \{yellow\}, \\ \{cyan, red, black\}, \{red, black\})$$

Then the second part of the algorithm would return an optimal solution which is, in this case, $H = (red, red, red, yellow, black, black)$, with $w(H) = 2$.

One can note that there can exist other optimal affectations, from [Figure 1](#) we can choose $H_2 = (cyan, yellow, yellow, yellow, red, red)$, but in any case, any other affectations will not be less than $w(H)$.

3.4 Extension on cycles

A cycle in a path whose starting node coincide with its last one. In this situation, the previous algorithm is no more effective, since we need to keep into account the potential color switch between the first and the last arcs. However, the procedure proposed in [Section 3.1](#), can be easily modified to provide an optimal affectation on cycles.

Let's take the path of [Figure 1](#) and imagine that nodes n_1 and n_7 coincide. The affectation H of [Section 3.3](#) is no more optimal since $w(H) = 3$, whereas the cost of the affectation $H' = (red, red, red, yellow, red, red)$ is 2.

In order to consider this situation, it is important to look at the intersection between the first and the last set of colors returned by the first part of the procedure. In particular, the subset associated to the extrema arcs of the path, will be modified into the intersection of their corresponding sets if non-empty. Finally we can apply second part of the algorithm.

Concretely, take the example in [Figure 1](#), we intersect H_{C1} with H_{C2} . Since this intersection \mathcal{I} is non-empty, then $H_{C1} \leftarrow \mathcal{I}$ and $H_{C7} \leftarrow \mathcal{I}$. The resulting affectation will be exactly H' which has the optimal cost.

4 Minimize color switches with matrices

The previous section provides a strategy to compute the smallest cost of a given path. It has been shown that an optimal strategy is to delay color switches as much as possible. In this section we reuse this concept in order to find paths with a *fixed* number of edges between two vertices minimizing the number of color switches.

4.1 Floyd-Warshall algorithm

Floyd [\[1\]](#) and Warshall [\[2\]](#), in respectively 1959 and 1962, gave an implementation [\[6\]](#) of an algorithm able to compute the shortest path between any pair of vertices of a directed weighted graph. The solution is found in polynomial time over the number of vertices of the graph.

In particular, let G be a directed graph and a cost function w , such that for all pair of vertices i, j of V , if there exists no arc going from i to j in A then $w(i, j) = \infty$ and for each $v \in V$, $w(v, v) = 0$. Let M be the $n \times n$ adjacency matrix of G such that each cell M_{ij} equals $w(i, j)$.

The goal of the algorithm is to build a new matrix N whose cells contains the weight of the shortest path for every pair of vertices. This matrix is updated iteratively: at time 0, we have $N^0 = M$ representing all the shortest path of length *at most* 1 between two vertices. This information should however be improved to find out paths of smaller length made of more than one arc. Therefore, for every pair $i, j \in V^2$, we seek if a shortest path from i to j passing through a third vertex k exists.

$$N_{ij} = \min_{k \in V} (N_{ik} + N_{kj}) \quad (2)$$

The second iteration, N^2 , computes all the shortest paths of length *at most* 2 for every pair of vertices. Globally, the matrix should be updated n times since, except for negative cycles, every shortest path between two vertices will pass through every vertex *at most* one time.

The overall time complexity of the Floyd-Warshall algorithm is $\mathcal{O}(n^3)$, we need to loop n times through a $n \times n$ matrix.

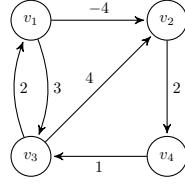


Figure 2: A directed weighted graph example

	v_1	v_2	v_3	v_4		v_1	v_2	v_3	v_4		v_1	v_2	v_3	v_4		v_1	v_2	v_3	v_4
v_1	0	-4	3	∞	v_1	0	-4	3	-2	v_1	0	-4	3	-2	v_1	0	-4	-1	-2
v_2	∞	0	∞	2	v_2	∞	0	∞	2	v_2	∞	0	∞	2	v_2	5	0	3	2
v_3	2	4	0	∞	v_3	2	-2	0	0	v_3	2	-2	0	0	v_3	2	-2	0	0
v_4	∞	∞	1	0	v_4	∞	∞	1	0	v_4	3	-1	1	0	v_4	3	-1	1	0

(a) Iteration 1 (b) Iteration 2 (c) Iteration 3 (d) Iteration 4

Table 1: Floyd-Warshall algorithm execution of Figure 2

Floyd-Warshall algorithm run Let's take the directed graph represented in Figure 2. The corresponding matrix M is indicated in Table 1a. At the iteration 4, the distance from the vertex v_1 to vertex v_3 is updated to -1 since there is a shorter path going from v_1 to v_4 and then from v_4 to v_3 . Its overall cost is given by $c_{1,4} + c_{4,3} = -2 + 1 = -1$ which is less than the direct path v_1 to v_3 .

4.2 Paths of fixed length with minimum cost

As explained in [7] and [8], the Floyd-Warshall algorithm can be generalized in order to compute shortest paths on directed weighted graphs having a *fixed* number of edges. This approach is based on the theory of semirings [3].

Semiring A *semiring*[9] is an algebraic structure composed by a set of elements R and two binary operators \oplus and \otimes . (R, \oplus) forms a commutative monoid with an identity element z . (R, \otimes) forms a monoid with an identity element called e , it is right distributive over \oplus and z is absorbing over \otimes . A semiring differs from a ring because it is not required to have an inverse for the \oplus operation.

Floyd-Warshall generalized algorithm Let M be the adjacency matrix of a graph whose cells on the diagonal have infinity weights if there is no self-loop on the considered vertex. We say that N^k is the matrix where each cell N_{ij} contains the cost of the shortest path from i to j with *exactly* k edges¹. The update function of this generalized approach differs from Equation (2) since the cost of the cell c_{ij} at time k will depend of the cost at the previous iteration and the adjacency matrix.

$$N_{ij}^k = \min_{v \in V} (N_{iv}^{k-1} + M_{vj}) \quad (3)$$

The time complexity of this computation is $\mathcal{O}(n^3k)$, since to pass from N^i to N^{i+1} we must read n time the $n \times n$ matrix and globally the matrix is updated k times.

Link with semirings It is possible to rewrite this equation in a more concise way using the definition of semiring. In fact, if, from Equation (3), the min operator is the \oplus and the $+$ operator is the \otimes . We have that $N^k = \oplus(N^{k-1} \otimes M)$. We can further simplify the notation and say that $N^k = N^{k-1} \odot M = M^{\odot k}$. Finally, since min and $+$ are associative, we can improve the previous complexity using the binary exponentiation [4] and get $\mathcal{O}(n^3 \log k)$.

4.3 Minimize color switches with matrices

In this section we propose an adaptation of the generalized Floyd-Warshall algorithm in order to compute shortest paths of fixed length minimizing the number of color switches in oriented graphs. This adaptation wants to merge this procedure with the idea of delaying color switches proposed in Section 3.1.

The adjacency matrix M is defined differently, since we do not have exact costs associated to arcs: the cost depends on the color of two adjacent color affectations. In our implementation, M is represented by the coloring function where $\text{colF}(ij) = \emptyset$ if there is no edge between the two vertices i and j .

¹Note that in Section 4.1 we spoke about path of *at most* k edges.

The cells of the N^0 matrix is a pair $(w, cols)$ where: w is the cost of the path and $cols$ is the set of colors minimizing the number of color switches for the path going for each vertex v_i to v_j .

Similarly to the matrix computation illustrated in the previous section, M^k depends on the matrix at time $k - 1$ and the coloring function (*i.e.* the modified adjacency matrix). For all $i, j \in V$, $N_{ij}^0 = \{w \leftarrow 0 \text{ if } \text{colF}(ij) \neq \emptyset; cols \leftarrow \text{colF}(ij)\}$. The N^{k+1} is computed by [Algorithm 1](#).

Algorithm 1: Compute N^{k+1}

Input: N^k , colF, respectively, the matrix at time k and the coloring function
Output: N^{k+1} the matrix at time $k + 1$

```

1  $n \leftarrow$  the number of vertices of the graph;
  // Matrix initialization
2  $N^{k+1} \leftarrow$  new  $n \times n$  matrix ;
3  $\forall i, j \in [0..n]^2 : N_{ij}^{k+1} \leftarrow \{w \leftarrow \infty; cols \leftarrow \emptyset\};$ 
  // Procedure start
4 for  $i = 1$  to  $n$  do
5   for  $j = 1$  to  $n$  do
6     for  $p = 1$  to  $n$  do
7        $\mathcal{I} \leftarrow N_{ip}^k.cols \cap \text{colF}(pj);$ 
8        $cost \leftarrow N_{ip}^k.w + (\text{if } \mathcal{I} = \emptyset \text{ then } 1 \text{ else } 0);$ 
9        $\mathcal{S} \leftarrow (\text{if } \mathcal{I} = \emptyset \text{ then } \text{colF}(pj) \text{ else } \mathcal{I});$ 
10      if  $cost < N_{ij}^{k+1}.w$  then
11         $N_{ij}^{k+1} \leftarrow \{w \leftarrow cost; cols \leftarrow \mathcal{S}\};$ 
12      else if  $cost = N_{ij}^{k+1}.w$  then
13         $N_{ij}^{k+1}.cols \leftarrow \mathcal{S} \cup N_{ij}^{k+1}.cols;$ 
14      end
15    end
16  end
17 end
18 return  $N^{k+1};$ 

```

Analyze of Algorithm 1 The first step of the algorithm is to initiate the resulting matrix N^{k+1} such that each cell as an empty set of colors and an infinity cost. After this initialization, we loop over each pair of vertices ij and, as for the generalized version of the Floyd-Warshall algorithm, we look for minimal paths passing through each vertex $p \in V$. This distance is obtained following the w function: if the intersection \mathcal{I} of $\text{colF}(pj)$ and the color set of cell ip of N^k is not empty, we are able to avoid a color switch and therefore, the cost of the path ip, pj is the same as the cost of the path ip . On the other hand, if the intersection is empty, the cost of the path will be 1 more than the cost of the path ip . \mathcal{S} is the set of colors that can be associated to the arc pj . It is equal to \mathcal{I} if \mathcal{I} is non-empty (*i.e.* we are delaying a color switch), otherwise, it will be affected to $\text{colF}(pj)$, since any color in $\text{colF}(pj)$ will not avoid a color switch.

Let $0 \leq p' \leq p \leq n$. While looping over all the intermediate vertex v_p , we can have three possible scenarios:

- there exists a path passing through $v_{p'}$ which is less than the path passing through v_p , the path through n_p can be ignored;
- the computed cost is strictly less than all the the previous path passing through $v_{p'}$, in this case the shortest path between ij will take this new cost and its set of colors will \mathcal{S} ;
- finally, the cost passing through v_i equals a previous minimal one. In this case, the cost is not updated, but the colors we can give to the edge ij , to reduce the possibility of a switch, will be the union of the colors of the previous best affectations and $mathcal{S}$.

5 Minimize colors switches with MDD

5.1 Multi-Valued Decision Diagram

A *Multi-Valued Decision Diagram* is

5.2 MDD strategy

5.3 The all different constraint

5.4 Find simple paths

5.5 The NValue constraint

6 My implementation

6.1 Algorithm comparison

7 Conclusion

8 References

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A Algorithms

A.1 Minimize color switches in a path

Algorithm 2: Shortest path of a path

Input: $P = (a_1, \dots, a_k)$, $\text{colF} :=$ a path and the color function
Output: $H :=$ a path affectation minimizing the color switches

```

1  $\text{colSet} \leftarrow [\text{colF}(a_i) \text{ for } i \in [1..k]];$ 
2 for  $i \leftarrow 2$  to  $k$  do
3    $\text{inter} \leftarrow \text{colSet}[i-1] \cap \text{colSet}[i];$  // Delay a color switch
4   if  $\text{inter} \neq \emptyset$  then
5      $\text{colSet}[i] \leftarrow \text{inter};$ 
6   end
7 end
8  $H \leftarrow [\text{colSet}[i].\text{choose}() \text{ for } i \in [1..k]];$ 
9 for  $i = k-2$  downto  $1$  do
10  if  $H[i+1] \in \text{colSet}[i] \wedge H[i] \neq H[i+1]$  then
11     $H[i] \leftarrow H[i+1];$  // If possible the  $R(e_i)$  equals  $R(e_{i+1})$ 
12  end
13 end
14 return  $H;$ 

```
