
An algorithm for Kolmogorov distance based approximation of discrete random variables

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Abstract

1 We present an algorithm that takes a discrete random variable X and a number m
2 and computes a random variable whose support (set of possible outcomes) is of
3 size at most m and whose Kolmogorov distance from X is minimal.

4 1 Introduction

5 Many different approaches to approximation of probability distributions are studied in the litera-
6 ture [12, 15, 16]. The approaches vary in the types random variables considered, how they are rep-
7 resented, and in the criteria used for evaluation of the quality of the approximations. This paper is
8 on approximating discrete distributions represented as explicit probability mass functions with ones
9 that are simpler to store and to manipulate. This is needed, for example, when a discrete distribution
10 is given as a large data-set, obtained, e.g., by sampling, and we want to represent it approximately
11 with a small table.

12 The main contribution of this paper is an efficient algorithm for computing the best possible ap-
13 proximation of a given random variable with a random variable whose complexity is not above a
14 prescribed threshold, where the measures of the quality of the approximation and the complexity of
15 the random variable are as specified in the following two paragraphs.

16 We measure the quality of an approximation by the distance between the original variable and the
17 approximate one. Specifically, we use the Kolmogorov distance which is commonly used for com-
18 paring random variables in statistical practice and literature. Given two random variables X and
19 X' whose cumulative distribution functions (cdfs) are F_X and $F_{X'}$, respectively, the Kolmogorov
20 distance between X and X' is $d_K(X, X') = \sup_t |F_X(t) - F_{X'}(t)|$ (see, e.g., [9]). We say that X'
21 is a good approximation of X if $d_K(X, X')$ is small.

22 The complexity of a random variable is measured by the size of its support, the number of values
23 that it can take, $|\text{support}(X)| = |\{x: \Pr(X = x) \neq 0\}|$. When distributions are maintained as
24 explicit tables, as done in many implementations of statistical software, the size of the support of
25 a variable is proportional to the amount of memory needed to store it and to the complexity of the
26 computations around it. In summary, the exact notion of optimality of the approximation targeted in
27 this paper is:

28 **Definition 1.** A random variable X' is an optimal m -approximation of a random variable X if
 29 $|\text{support}(X')| \leq m$ and there is no random variable X'' such that $|\text{support}(X'')| \leq m$ and
 30 $d_K(X, X'') < d_K(X, X')$.

31 The main contribution of the paper is an efficient algorithm that takes X and m as parameters and
 32 constructs an optimal m -approximation of X .

33 The rest of the paper is organized as follows. In Section 2 we describe how our work relates to other
 34 algorithms and problems studied in the literature. In Section 3 we detail the proposed algorithm,
 35 analyze its properties, and prove the main theorem. In Section 4 we demonstrate how the proposed
 36 approach performs on the problem of estimating the probability of hitting deadlines in plans and
 37 compare it to alternatives approximation approaches from the literature. We also demonstrate the
 38 performance of our approximation algorithm on some randomly generated random variables. The
 39 paper is concluded with a discussion in Section 5.

40 2 Related Work

41 The most relevant work related to this paper is the papers by Cohen et. al. [5, 4]. These papers study
 42 approximations of random variables in the context of estimating deadlines. In this context, X' is
 43 defined to be a good approximation of X if $F_{X'}(t) > F_X(t)$ for any t and $\sup_t F_{X'}(t) - F_X(t)$
 44 is small. This is not a distance because it is not symmetric. The motivation given by Cohen et. al.
 45 for using this notion is for cases where overestimation of the probability of missing a deadline is
 46 acceptable but underestimation is not. In Section 4, we consider the same examples examined by
 47 Cohen et. al. and show how the algorithm proposed in this paper performs relative to the algorithms
 48 proposed there when both over- and under- estimations are allowed. As expected, the Kolmogorov
 49 distance between the approximation and the original random variable is smaller by a factor of one
 50 half, on average.

51 Another very relevant work is the theory of Sparse Approximation (aka Sparse Representation) that
 52 deals with sparse solutions for systems of linear equations, as follows.

Given a matrix $D \in \mathbb{R}^{n \times p}$ and a vector $x \in \mathbb{R}^n$, the most studied sparse representation problem is
 finding the sparsest possible representation $\alpha \in \mathbb{R}^p$ satisfying $x = D\alpha$:

$$\min_{\alpha \in \mathbb{R}^p} \|\alpha\|_0 \text{ subject to } x = D\alpha.$$

53 where $\|\alpha\|_0 = |\{i : \alpha_i \neq 0, i = 1, \dots, p\}|$ is the ℓ_0 pseudo-norm, counting the number of non-zero
 54 coordinates of α . This problem is known to be NP-Hard with a reduction to NP-complete subset
 55 selection problems.

In these terms, using also the ℓ_∞ norm that represents the maximal coordinate and the ℓ_1 norm that
 represents the sum of the coordinates, our problem can be phrased as:

$$\min_{\alpha \in [0, \infty)^p} \|x - D\alpha\|_\infty \text{ subject to } \|\alpha\|_0 = m \text{ and } \|\alpha\|_1 = 1.$$

56 where D is the all-ones triangular matrix (the entry at row i and column j is one if $i \leq j$ and zero
 57 otherwise), x is related to X such that the i th coordinate of x is $F_X(x_i)$ where $\text{support}(X) =$
 58 $\{x_1 < x_2 < \dots < x_n\}$ and α is related to X' such that the i th coordinate of α is $f_{X'}(x_i)$. The
 59 functions F_X and $f_{X'}$ represent, respectively, the cumulative distribution function of X and the
 60 mass distribution function of X' . This, of course, means that the coordinates of x are assumed to
 61 be positive and monotonically increasing and that the last coordinate of x is assumed to be one. We

62 demonstrate an application for this specific sparse representation problem and show that it can be
 63 solve in $O(n^2m)$ time and $O(m^2)$ memory.

64 Another related research is binning in statistical inference. Consider, for example, the problem
 65 of credit scoring [21] that deals with separating good applicants from bad applicants where the
 66 Kolmogorov–Smirnov statistic KS is a standard measure. The KS comparison is often preceded
 67 by a procedure called binning where a large table is shrunk to a smaller one by collecting nearby
 68 values together. There are many methods for binning [11, 17, 2, 19]. In this context, our algorithm
 69 can be consider as a new binning strategy that provides optimality guarantees with respect to the
 70 Kolmogorov distance that none of the existing binning technique that we are aware of provides.

71 The present study is also related to the work of Pavlikov and Uryasev [15], where a procedure for
 72 producing a random variable X' that optimally approximates a random variable X is presented.
 73 Their approximation scheme, achieved using convex and linear programming, is designed for a
 74 different notion of distance (called CVaR). The new contribution of the present work in this context
 75 is that our method is direct, not using linear or convex programming, thus allowing tighter analysis
 76 of time and memory complexity. Also, our method is designed for optimizing the Kolmogorov
 77 distance that is more prevalent in applications.

78 3 An Algorithm for Optimal Approximation

79 In the scope of this section, let X be a given random variable with a finite support of size n , and let
 80 $0 < m \leq n$ be a given complexity bound. We first develop notations and collect facts towards an
 81 algorithm for finding an optimal m -approximation of X .

82 The first useful fact is that it is enough to limit our search to approximations X' 's such that
 83 $\text{support}(X') \subseteq \text{support}(X)$:

84 **Lemma 2.** *For every random variable X'' there is a random variable X' such that $\text{support}(X') \subseteq$
 85 $\text{support}(X)$ and $d_K(X, X') \leq d_K(X, X'')$.*

86 *Proof.* Let X'' be a random variable whose support is of size smaller or equal to m . We find a
 87 random variable X' with $\text{support}(X') \subseteq \text{support}(X)$ such that $d_K(X, X') \leq d_K(X, X'')$. Let
 88 $\{x_1, \dots, x_n\} = \text{support}(X)$, and let $x_0 = -\infty, x_{n+1} = \infty$. Consider the random variable X'
 89 whose probability mass function is $f_{X'}(x_i) = P(x_{i-1} < X'' \leq x_i)$ for $i = 1, \dots, n-1$, $f_{X'}(x_n) =$
 90 $P(x_n - 1 < X'' < x_{n+1})$, and $F_{X'}(x) = 0$ if $x \notin \text{support}(X)$. Since X' "accumulates" the non-
 91 zero probabilities of X'' to the support of X , we have that f is a probability mass function and
 92 therefore X' is well defined.

93 First see by construction that $|F_X(x_i) - F_{X'}(x_i)| = |F_X(x_i) - F_{X''}(x_i)|$ for every $1 \leq i \leq n-1$.
 94 For $i = n$ we have $|F_X(x_n) - F_{X'}(x_n)| = |1 - 1| = 0$. Finally see that $|F_X(x) - F_{X'}(x)| =$
 95 $|F_X(x_i) - F_{X'}(x_i)|$ for every $0 \leq i < n+1$ and $x_i < x < x_{i+1}$. Therefore we have that
 96 $d_K(X, X') = \max_i |F_X(x_i) - F_{X'}(x_i)| \leq \max_i |F_X(x_i) - F_{X''}(x_i)| \leq d_K(X, X'')$. \square

97 Next, note that every random variable X'' with support of size at most m that is contained in
 98 $\text{support}(X)$ can be described by first setting the (at most m) elements of the support of X'' ; then
 99 for every such option, determine X'' by setting probability values for the elements in the chosen
 100 support of X' , and setting 0 for rest of the elements.

101 Denote the set of random variables with support $S \subseteq \text{support}(X)$ by \mathbb{X}_S . In Step 1 below, we find
 102 a random variable in \mathbb{X}_S that minimizes the Kolmogorov distance from X , and denote this distance

by $\varepsilon(X, S)$. Next, in Step 2, that we will describe later, we will show how to efficiently find S that minimizes $\varepsilon(X, S)$ among all the sets that satisfy $S \subset \text{support}(X)$ and $|S| \leq m$. Then the minimized random variable \mathbb{X}_S from the minimal S , is the m -optimal approximation to X .

Step 1: Finding an X' in \mathbb{X}_S that minimizes $d_K(X, X')$

We first fix a set $S \subseteq \text{support}(X)$ of size at most m , and among all the random variables in \mathbb{X}_S find one with a minimal distance from X . Denote the elements of S in increasing order by $S = \{x_1 < \dots < x_m\}$ and let $x_0 = -\infty$, and $x_{m+1} = \infty$. For every $1 \leq i \leq m$ let \hat{x}_i be the maximal element of $\text{support}(X)$ that is smaller than x_i .

Next, as the elements of S are also elements of $\text{support}(X)$, we can define the following weight function:

Definition 3. For $0 \leq i \leq m$ let

$$w(x_i, x_{i+1}) = \begin{cases} P(x_i < X < x_{i+1}) & \text{if } i = 0 \text{ or } i = m; \\ P(x_i < X < x_{i+1})/2 & \text{otherwise.} \end{cases}$$

Note that $x_i = -\infty$ for $i = 0$ and $x_i = \infty$ for $i = m + 1$. Also note that $P(x_i < X < x_{i+1}) = F_X(\hat{x}_{i+1}) - F_X(x_i)$, a fact that we will use throughout this section.

Definition 4. Let $\varepsilon(X, S) = \max_{i=0, \dots, m} w(x_i, x_{i+1})$.

We first show that $\varepsilon(X, S)$ is a lower bound. That is, every random variable in \mathbb{X}_S has a distance at least $\varepsilon(X, S)$. Then, we present a random variable $X' \in \mathbb{X}_S$ with distance $\varepsilon(X, S)$. It then follows that such X' is an optimal m -approximation random variable among all random variables in \mathbb{X}_S .

The intuition behind choosing these specific weights and $\varepsilon(X, S)$ being a lower bound is as follows. Since for every $X' \in \mathbb{X}_S$ the probability values of X' for the elements not in S are set to 0, we have that $F_{X'}(\hat{x}_{i+1}) = F_{X'}(x_i)$. Therefore the distance between X' and X at points x_i and \hat{x}_{i+1} that we have to take into additional account is increased by $F_X(\hat{x}_{i+1}) - F_X(x_i) = P(x_i < X < x_{i+1})$.

Formally we have the following.

Proposition 5. If $X' \in \mathbb{X}_S$ then $d_K(X, X') \geq \varepsilon(X, S)$.

Proof. By definition, for every $0 \leq i \leq m$, $d_K(X, X') \geq \max\{|F_X(\hat{x}_{i+1}) - F_{X'}(\hat{x}_{i+1})|, |F_X(x_i) - F_{X'}(x_i)|\}$. Note that $F_{X'}(\hat{x}_{i+1}) = F_{X'}(x_i)$ since the probability values for all the elements not in S are set to 0.

If $i = 0$, that is $x_i = -\infty$, we have that $F_X(x_i) = F_{X'}(x_i) = F_{X'}(\hat{x}_{i+1}) = 0$ and therefore $d_K(X, X') \geq |F_X(\hat{x}_{i+1})| = |F_X(\hat{x}_{i+1}) - F_X(x_i)| = P(x_i < X < x_{i+1}) = w(x_i, x_{i+1})$.

If $i = m$, that is $x_{i+1} = \infty$, we have that $F_X(\hat{x}_{i+1}) = F_{X'}(\hat{x}_{i+1}) = F_{X'}(x_i) = 1$. and therefore $d_K(X, X') \geq |1 - F_X(\hat{x}_i)| = |F_X(\hat{x}_{i+1}) - F_X(x_i)| = P(x_i < X < x_{i+1}) = w(x_i, x_{i+1})$.

Otherwise for every $1 \leq i < m$, we use the fact that $\max\{|a|, |b|\} \geq |a - b|/2$ for every $a, b \in \mathbb{R}$, to have $d_K(X, X') \geq 1/2|F_X(\hat{x}_{i+1}) - F_X(x_i) + F_{X'}(x_i) - F_{X'}(\hat{x}_{i+1})|$. So $d_K(X, X') \geq 1/2|F_X(\hat{x}_{i+1}) - F_X(x_i)| = P(x_i < X < x_{i+1})/2 = w(x_i, x_{i+1})$.

Therefore since $d_K(X, X') \geq w(x_i, x_{i+1})$ for every $0 \leq i \leq m$, by definition of $\varepsilon(X, S)$ proof follows. \square

Next we show a random variable $X' \in \mathbb{X}_S$ with a distance of $\varepsilon(X, S)$ from X . Thus X' is an optimal m -approximation among the set \mathbb{X}_S . We define X' as follows:

Definition 6. Let $f_{X'}(x_i) = w(x_{i-1}, x_i) + w(x_i, x_{i+1}) + f_X(x_i)$ for $i = 1, \dots, m$ and $f_{X'}(x) = 0$ for $x \notin S$.

We first show that X' is a properly defined random variable:

Lemma 7. $f_{X'}$ is a probability mass function.

Proof. From definition $f_{X'}(x_i) \geq 0$ for every i . To see that $\sum_i f_{X'}(x_i) = 1$, we have
 $\sum_i f_{X'}(x_i) = \sum_i (w(x_{i-1}, x_i) + w(x_i, x_{i+1}) + f_X(x_i)) = \sum_{x_i \in S} f_X(x_i) + w(x_0, x_1) + \sum_{0 < i < m} 2w(x_i, x_{i+1}) + w(x_m, x_{m+1}) = \sum_{x_i \in S} P(X = x_i) + P(x_0 < X < X_1) + \sum_{0 < i < m} P(x_i < X < X_{i+1}) + P(x_m < X < X_{m+1}) = 1$ since this sum is the entire cdf of X . \square

Note that X' can be constructed in linear time to the size of the cdf of X . Intuitively the setting of X' allows to take an "advantage" of distance from X at the elements of $\text{support}(X')$, to avoid the overall increased distance of X from X' at the elements that are not at $\text{support}(X)$ and in which $f_{X'}$ is set to 0. Formally we have the following.

Lemma 8. Let $x \in \text{support}(X)$ and $0 \leq i \leq m$ be such that $x_i \leq x \leq x_{i+1}$ then $-w(x_i, x_{i+1}) \leq F_X(x) - F_{X'}(x) \leq w(x_i, x_{i+1})$.

Proof. We prove by induction on $0 \leq i < m$.

First see that $F_{X'}(j) = 0$ for every $x_0 < j < x_1$ and therefore $F_X(j) - F_{X'}(j) = F_X(j) - 0 \leq F_X(\hat{x}_1) = F_X(\hat{x}_1) - F_X(x_0) = w(x_0, x_1)$. For $j = x_1$ we have $F_X(x_1) - F_{X'}(x_1) = F_X(\hat{x}_1) + f_X(x_1) - (w(x_0, x_1) + w(x_1, x_2) + f_X(x_1)) = w(x_0, x_1) + f_X(x_1) - (w(x_0, x_1) + w(x_1, x_2) + f_X(x_1)) = -w(x_1, x_2)$.

Next assume that $F_X(\hat{x}_i) - F_{X'}(\hat{x}_i) = w(x_{i-1}, x_i)$. Then $F_X(x_i) - F_{X'}(x_i) = F_X(\hat{x}_i) + f_X(x_i) - (w(x_{i-1}, x_i) + w(x_i, x_{i+1}) + f_X(x_i)) = w(x_{i-1}, x_i) + f_X(x_i) - (w(x_{i-1}, x_i) + w(x_i, x_{i+1}) + f_X(x_i)) = -w(x_i, x_{i+1})$.

As before we have that for all $x_i < j < x_{i+1}$, we have $F_X(j) - F_{X'}(j) = F_X(j) - F_{X'}(\hat{x}_{i+1}) \leq F_X(\hat{x}_{i+1}) - F_{X'}(\hat{x}_{i+1})$. Then $F_X(\hat{x}_{i+1}) - F_{X'}(\hat{x}_{i+1}) = (F_X(x_i) + P(x_i < x < x_{i+1})) - F_{X'}(x_i) = -w(x_i, x_{i+1}) + 2w(x_i, x_{i+1}) = w(x_i, x_{i+1})$.

Finally for $x_m \leq j \leq x_{m+1}$ we have that $F_{X'}(x_m) = 1$ therefore $F_X(x_m) - F_{X'}(x_m) = (1 - P(x_m < X < x_{m+1})) - 1 = P(x_m < X < x_{m+1}) = w(x_m, x_{m+1})$, and for every $x_m < j < x_{m+1}$ we have $F_X(j) - F_{X'}(j) < (1 - P(x_m < X < x_{m+1})) - 1 < -P(x_m < X < x_{m+1}) = -w(x_m, x_{m+1})$ as required. \square

From Lemma 8, by the definition of $\varepsilon(X, S)$, we then have:

Corollary 9. $d_K(X, X') = \varepsilon(X, S)$.

Step 2: Finding a set S that minimizes $\varepsilon(X, S)$

Finding the m -optimal random variable with a distance $\varepsilon(X, S)$ among the set \mathbb{X}_S , we next proceed to find an S that minimizes $\varepsilon(X, S)$. To obtain that we use a dynamic programming approach, motivated by a method described in [3]. Intuitively we construct a directed graph with a source and a target, in which every (acyclic) source-target path of size $\leq m$ corresponds to a possible support

set of the same size, and the weights along that path correspond to the weight as defined in Definition 3. Thus the problem of finding the S that minimizes $\varepsilon(X, S)$ is reduced to the problem of finding the source-target path \vec{p} of size $\leq m$ in that graph such that the maximal weight of an edge in \vec{p} is minimal among all other such maximal edges in all other paths of size $\leq m$.

In details, we initially constructs a directed weighted graph $G = (V, E, s, t, w)$, where $V = v_0, \dots, v_{n+1}$ correspond to the support of X with the additional $v_0 = s$ as the source vertex and $v_{n+1} = t$ as the target vertex. We set an edge (v_i, v_j) for every $i < j$ and a weight that is defined as follows. If $1 < i < j < n$ then $w(v_i, v_j) = P(x_i < X < x_{i+1})/2$. For $i = 0$ or $j = n + 1$ we set $w(v_i, v_j) = P(x_i < X < x_{i+1})$. Thus the weight of every edge (i, j) corresponds to Definition 3 for a case in which x_i, x_j where consecutive elements in an optional set S of size $\leq m$. Note that there is a 1-1 correspondence between a subset S of $\text{support}(X)$ of size m , and an $s-t$ path \vec{p}_S in G where every $x_i \in S$ corresponds to the vertex $v_i \in \vec{p}_S$. On that sense note that the maximal weight of an edge on \vec{p}_S is identical to $\varepsilon(X, S)$. We denote this maximal weight of an edge by $w(\vec{p}_S)$, and denote the set of all acyclic s -to- t paths in G with at most m edges is called $\text{paths}_m(G, s, t)$. Thus, the problem of finding the set S with the minimal $\varepsilon(X, S)$ is trivially reduced to the problem of finding a path $\vec{p} \in \text{paths}_m(G, s, t)$ such that $w(\vec{p})$ is minimal among all $\{w(\vec{p}') | \vec{p}' \in \text{paths}_m(G, s, t)\}$. This problem can be solved by the standard Bellman-Ford algorithm in m iterations (e.g. [10, 18]) denoted by $\text{BellmanFord}(G, m)$. We thus have the following from the standard Bellman-Ford technique.

Corollary 10. *$\text{BellmanFord}(G, m)$ returns a path $\vec{p} \in \text{paths}_m(G, s, t)$ such that $w(\vec{p})$ is minimal among all $\{w(\vec{p}') | \vec{p}' \in \text{paths}_m(G, s, t)\}$.*

Constructing the overall algorithm

We combine Step 1 and Step 2 in the following algorithm called KolmogorovApprox (Algorithm 1) that follows naturally from the two steps. Given X and $\text{support}(X)$ we add x_0, x_{n+1} and construct the graph (line 2) as in Step 2. Then we execute the Bellman-Ford algorithm on G for m iterations to obtained a path $\vec{p} = (v_0, \dots, v_{m+1})$ (line 2) as described in Corollary 10. Finally we use Definition 6 to construct X' from the weights of \vec{p} (lines 4-5).

Algorithm 1: KolmogorovApprox(X, m)

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1  $\text{support}(X) \cup \{x_0, x_{n+1}\}$ 
2 Construct  $G = (V, E, s, t, w)$  according to Step 2
3  $\vec{p} = (v_0, \dots, v_{m+1}) = \text{Bellman} - \text{Ford}(G, m)$ 
4 for  $0 < i < m + 1$  do
5    $f_{X'}(x_i) = w(v_{i-1}, v_i) + w(v_i, v_{i+1}) + f_X(x_i)$ 
6 return  $X'$ 

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Theorem 11. *KolmogorovApprox returns an m -optimal-approximation of X .*

Proof. From Corollary 10 and the construction of G we get that the path \vec{p} obtained in line 4 of KolmogorovApprox describes a set S of support os size at most m for which ε_S, X is minimal. Then from Definition 6 and Corollary 9 we construct X' in lines 4-5 of KolmogorovApprox such that $d_K(X, X') = \varepsilon(X, S)$. Therefore X' is an m -approximation among all random variables with support contained in $\text{support}(X)$. Finally from Lemma 2 we have that X' is m -approximation among all random variables os support of size at most m , thus X' is an m -optimal-approximation of X . \square

212 Finally we analyze the complexity of KolmogorovApprox as follows.

213 **Theorem 12.** *The KolmogorovApprox(X, m) algorithm runs in time $O(mn^2)$, using $O(n^2)$ mem-*
 214 *ory where $n = |\text{support}(X)|$.*

215 *Proof.* Constructing the graph G as described in Step 2 takes $O(n^2)$. The number of edges in G
 216 is $O(|E|) = O(n^2)$, for every edge the weight is at most the sum of all probabilities between the
 217 source node s and the target node t , which can be calculated efficiently by aggregating the weights
 218 of already calculated edges. The construction is also the only stage that requires memory allocation,
 219 specifically $O(|E| + |V|) = O(n^2)$. Next using the Bellman-Ford algorithm on G for m iterations
 220 takes $O(m(|E| + |V|)) \approx O(mn^2)$. [[DF: cite Corman or some algorithms book]]. Finally deriving
 221 the new random variable X' from the computed path \vec{p} takes $O(m)$ time: For every node x_i in \vec{p}
 222 (at most m nodes), use the already calculated weights to find the probability mass function $f_{X'}(x_i)$.
 223 To conclude, the time complexity of KolmogorovApprox(X, m) is $O(n^2 + mn^2 + m) = O(mn^2)$
 224 and memory complexity is $O(E + V) = O(n^2)$.

225 [[GW: put a reference to the work of the fellows from the Technion to avoid some of this?]]

226

□

227 4 A case study and experimental results

228 The case study examined in our experiments is the problem of task trees with deadlines [5, 4].
 229 Hierarchical planning is a well-established field in AI [6, 7, 8], and is still relevant nowadays [1,
 230 20]. A hierarchical plan is a method for representing problems of automated planning in which
 231 the dependency among tasks can be given in the form of networks, here we focus on hierarchical
 232 plans represented by task trees. The leaves in a task tree are *primitive* actions (or tasks), and the
 233 internal nodes are either *sequence* or *parallel* actions. The plans we deal with are of stochastic
 234 nature, and the task duration is described as probability distributions in the leaf nodes. We assume
 235 that the distributions are independent but *not* necessarily identically distributed and that the random
 236 variables are discrete and have a finite support.

237 A sequence node denotes a series of tasks that should be performed consecutively, whereas a parallel
 238 node denotes a set of tasks that begin at the same time. A *valid* plan is one that is fulfilled before
 239 some given *deadline*, i.e., its *makespan* is less than or equal to the deadline. The objective in this
 240 context is to compute the probability that a given plan is valid, or more formally computing $P(X <$
 241 $T)$, where X is a random variable representing the makespan of the plan and T is the deadline. The
 242 problem of finding the probability that a task tree satisfies a deadline is known to be NP-hard. In
 243 fact, even the problem of summing a set of random variables is NP-hard [13]. This is an example of
 244 an explicitly given random variable that we need to estimate deadline meeting probabilities for.

245 The first experiment we focus on is the problem of task trees with deadlines, and consider three
 246 types of task trees. The first type includes logistic problems of transporting packages by trucks and
 247 airplanes (from IPC2 <http://ipc.icaps-conference.org/>). Hierarchical plans of those logistic problems
 248 were generated by the JSHOP2 planner [14], one parallel node with all descendant task nodes being
 249 in sequence. The second type consists of task trees used as execution plans for the ROBIL team
 250 entry in the DARPA robotics challenge (DRC simulation phase), and the third type is of linear plans
 251 (sequential task trees). The primitive tasks in all the trees are modeled as discrete random variables
 252 with support of size M obtained by discretization of uniform distributions over various intervals.
 253 The number of tasks in a tree is denoted by N .

We implemented the approximation algorithm for solving the deadline problem with four different methods of approximation. The first two are for achieving a one-sided Kolmogorov approximation – the OptTrim [4] and the Trim [5] operators, and the third is a simple sampling scheme. We used those methods as a comparison to the Kolmogorov approximation with the suggested KolmogorovApprox algorithm. The parameter m of OptTrim and KolmogorovApprox corresponds to the inverse of ε given to the Trim operator. Note that in order to obtain some error ε , one must take into consideration the size of the task tree N , therefore, $m/N = 1/(\varepsilon \cdot N)$. We ran also an exact computation as a reference to the approximated one in order to calculate the error. The experiments conducted with the following operators and their parameters: KolmogorovApprox operator with $m = 10 \cdot N$, the OptTrim operator with $m = 10 \cdot N$, the Trim as operator with $\varepsilon = 0.1/N$, and two simple simulations, with a different samples number $s = 10^4$ and $s = 10^6$.

Task Tree	M	KolmogorovApprox	OptTrim	Trim	Sampling	
		$m/N=10$	$m/N=10$	$\varepsilon \cdot N=0.1$	$s=10^4$	$s=10^6$
Logistics ($N=34$)	2	0	0	0.0019	0.007	0.0009
	4	0.0024	0.0046	0.0068	0.0057	0.0005
Logistics ($N=45$)	2	0.0002	0.0005	0.002	0.015	0.001
	4	0	0.003	0.004	0.008	0.0006
DRC-Drive ($N=47$)	2	0.0014	0.004	0.009	0.0072	0.0009
	4	0.001	0.008	0.019	0.0075	0.0011
Sequential ($N=10$)	2	0.0093	0.015	0.024	0.0063	0.0008
	4	0.008	0.024	0.04	0.008	0.0016

Table 1: Comparison of estimated errors with respect to the reference exact computation on various task trees.

Table 1 shows the results of the case study experiment. The quality of the solutions provided by using the KolmogorovApprox operator are better than those provided by the Trim and OptTrim operators, following the optimality guarantees, but is interesting to see that the quality gaps happen in practice in each of the examined task trees. However, in some of the task trees the sampling method produced better results than the approximation algorithm with KolmogorovApprox. Nevertheless, the approximation algorithm comes with an inherent advantage of providing an exact quality guarantees, as opposed to the probabilistic guarantees provided by sampling.

In order to better understand the quality gaps in practice between KolmogorovApprox, OptTrim, and Trim, we investigate their relative errors when applied on single random variables with support size $n = 100$, and different support sizes of the resulting random variable approximation (m). In each instance of this experiment, a random variable is randomly generated by choosing the probabilities of each element in the support uniformly and then normalizing these probabilities so that they sum to 1.

Figure 1 present the error produced by the above methods. The depicted results are averages over several instances (50 instances) of random variables. The curves in the figure show the average error of OptTrim and Trim operators with comparison to the average error of the optimal approximation provided by KolmogorovApprox as a function of m . According to the depicted results it is evident that increasing the support size of the approximation m reduces the error, as expected, in all three methods. However, errors produced by the KolmogorovApprox are significantly smaller, a half of the error produced by OptTrim and Trim.

We also examined how our algorithm compares to linear programming as described and discussed, for example, in [15]. We ran an experiment to compare the run-time between the KolmogorovApprox algorithm with the run-time of a state-of-art implementation of linear programming. We used the

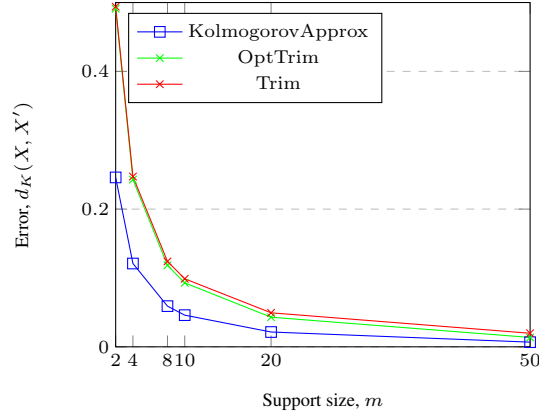


Figure 1: Error comparison between KolmogorovApprox, OptTrim, and Trim, on randomly generated random variables as function of m .

288 “Minimize” function of Wolfram Mathematica and fed it with the equations $\min_{\alpha \in \mathbb{R}^n} \|x - \alpha\|_\infty$
 289 subject to $\|\alpha\|_0 \leq m$ and $\|\alpha\|_1 = 1$. The run-time comparison results were clear and persuasive,
 290 for a random variable with support size $n = 10$ and $m = 5$, the LP algorithm run-time was 850
 291 seconds, where the KolmogorovApprox algorithm run-time was less than a tenth of a second. For
 292 $n = 100$ and $m = 5$, the KolmogorovApprox algorithm run-time was 0.14 seconds and the LP
 293 algorithm took more than a day. Due to these timing results of the LP algorithm we did not proceed
 294 to examine it any further. Since it is not trivial to formally analyze the run-time of the LP algorithm,
 295 we conclude by the reported experiment that in this case the LP algorithm might not be as efficient
 296 as KolmogorovApprox algorithm whose complexity is proven to be polynomial in Theorem 12.

297 5 Discussion

298 Compact representations of distributions is mentioned in the literature in various contexts for various
 299 applications. In this paper, we are interested in finding optimal approximation of a random variables
 300 under the Kolmogorov metric which we define as optimal m -approximation. In order to achieve
 301 this optimal approximation two steps were taken, find the support of the optimal random variable
 302 and then calculate the pmf of each and every value in that support to minimize the error. Proofs of
 303 existences, optimality and run-time were detailed in Section 3 and the main algorithm was presented,
 304 the KolmogorovApprox algorithm. Establishing the main contribution of this paper which is to
 305 present an optimal approximation scheme and to show it can be achieved in polynomial run-time.
 306 Furthermore, empirical evaluation was conducted on different domains and application to examine
 307 the algorithm performance in practice. We were interested in two aspects of performance - accuracy
 308 and run-time. Regarding to accuracy, as expected, the suggested KolmogorovApprox algorithm
 309 results much smaller error compared to the other methods, sometimes, in more then factor of 2.
 310 Regarding to run-time, KolmogorovApprox algorithm run-time is significantly much faster then
 311 LP approach. However, compared to other approximation methods accuracy vs. run-time is a trade
 312 off yet to be examined. Another interesting experiment that can be conducted in future work is to
 313 add the presented approach as one of the methods examined in [21] and compare it to the binning
 314 approaches.

315 As elaborated in the paper, our algorithm improves on the approach of Cohen, Shimony and
 316 Weiss [5] and [4] in that it finds an optimal two sided Kolmogorov approximation, and not just
 317 one sided. We consider this paper as a step in the examination of algorithms for optimal approxi-

318 mations of random variables. Beyond the Kolmogorov measure studied here we believe that similar
 319 approaches may apply also to total variation, the Wasserstein distance, and to other measures of
 320 approximations for other purposes.

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