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# Kolmogorov Approximation

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## 1 Introduction

Many different approaches to approximation of probability distributions are studied in the literature [9, 12, 13]. The papers vary in the types random variables involved, how they are represented, and in the criteria used for evaluation of the quality of the approximations. This paper is on approximating discrete distributions represented as explicit probability mass functions with ones that are simpler to store and to manipulate. This is needed, for example, when a discrete distribution is given as a large data-set, obtained, e.g., by sampling, and we want to represent it approximately with a small table.

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

We measure the quality of an approximation by the distance between the original variable and the approximate one. Specifically, we use the Kolmogorov distance which is one of the most used in statistical practice and literature. Given two random variables  $X$  and  $X'$  whose cumulative distribution functions (cdfs) are  $F_X$  and  $F_{X'}$ , respectively, the Kolmogorov distance between  $X$  and  $X'$  is  $d_K(X, X') = \sup_t |F_X(t) - F_{X'}(t)|$  (see, e.g., [8]). We say that  $X'$  is a good approximation of  $X$  if  $d_K(X, X')$  is small.

The complexity of a random variable is measured by the size of its support, the number of values that it can take,  $|\text{support}(X)| = |\{x: \Pr(X = x) \neq 0\}|$ . When distributions are maintained as explicit tables, as done in many implementations of statistical software, the size of the support of a variable is proportional to the amount of memory needed to store it and to the complexity of the computations around it.

In summary, the exact notion of optimality of the approximation targeted in this paper is:

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

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

The rest of the paper is organized as follows. In Section 2 we describe how our work relates to other algorithms and problems studied in the literature. In Section 3 we detail the proposed algorithm,

analyze its properties, and prove Theorem ???. In Section 4 we demonstrate how the proposed approach performs on the problem of estimating the probability of hitting deadlines is plans and compare it to alternatives approximation approaches from the literature. We also demonstrate the performance of our approximation algorithm on some randomly generated random variables. The paper is concluded with a discussion in Section 5.

## 2 Related Work

The problem studied in this paper is related to the theory of Sparse Approximation (aka Sparse Representation) that 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  $x = D\alpha$ :

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

where  $\|\alpha\|_0 = |\{i : \alpha_i \neq 0, i = 1, \dots, p\}|$  is the  $\ell_0$  pseudo-norm, counting the number of non-zero coordinates of  $\alpha$ . This problem is known to be NP-Hard with a reduction to NP-complete subset selection problems.

In these terms, using also the  $\ell_\infty$  norm that represents the maximal coordinate and the  $\ell_1$  norm that represents the sum of the coordinates, our problem can be phrased as:

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

where  $D$  is the all-ones triangular matrix (the entry at row  $i$  and column  $j$  is one if  $i \leq j$  and zero otherwise),  $x$  is related to  $X$  such that the  $i$ th coordinate of  $x$  is  $F_X(x_i)$  where  $\text{support}(X) = \{x_1 < x_2 < \dots < x_n\}$  and  $\alpha$  is related to  $X'$  such that the  $i$ th coordinate of  $\alpha$  is  $f_{X'}(x_i)$ . The functions  $F_X$  and  $f_{X'}$  represent, respectively, the cumulative distribution function of  $X$  and the mass distribution function of  $X'$ . This, of course, means that the coordinates of  $x$  are assumed to be positive and monotonically increasing and that the last coordinate of  $x$  is assumed to be one. We demonstrate an application for this specific sparse representation problem and show that it can be solve in  $O(n^2m)$  time and  $O(m^2)$  memory.

## 3 An Algorithm for Optimal Approximation

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

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

**Lemma 2.** *There is an optimal  $m$ -approximation  $X'$  of  $X$  such that  $\text{support}(X') \subseteq \text{support}(X)$ .*

*Proof.* Since minimizing  $d_K(X, X')$  subject to the constraints that  $\text{support}(X') \subseteq \text{support}(X)$  and  $|\text{support}(X')| \leq m$  is a convex optimization problem, it has a solution  $\varepsilon$ . Let  $X''$  be any random variable whose support is of size smaller or equal to  $m$ , let  $\{x_1, \dots, x_n\} = \text{support}(X)$ , and let  $x_{n+1} = \infty$ . Consider the the random variable  $X'$  whose probability mass function is  $f_{X'}(x_i) = P(x_i \leq X'' < x_{i+1})$  for  $i = 1, \dots, n$  and  $F_{X'}(x) = 0$  if  $x \notin \text{support}(X)$ . By definition  $d_K(X, X') = d_K(X, X'')$ . Since  $\text{support}(X') \subseteq \text{support}(X)$  and  $|\text{support}(X')| <$

63  $|\text{support}(X'')| \leq m$ , we get that  $d_K(X, X'') \geq \varepsilon$ . Thus,  $\varepsilon$  is a global minimum and any  
 64  $X' \in \text{argmin}\{d_K(X, X') : \text{support}(X') \subseteq \text{support}(X), |\text{support}(X')| \leq m\}$  is an  $m$ -optimal  
 65 approximation of  $X$ .  $\square$

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

70 Denote the set of random variables with support  $S \subset \text{support}(X)$  by  $\mathbb{X}_S$ . In Step 1 below, we find a  
 71 random variable in  $\mathbb{X}_S$  that minimizes the Kolmogorov distance from  $X$ , and denote this distance  
 72 by  $\varepsilon(X, S)$ . Next, in Step 2, that we will describe later, we will show how to efficiently find  $S$  that  
 73 minimizes  $\varepsilon(X, S)$  among all the sets that satisfy  $S \subset \text{support}(X)$  and  $|S| \leq m$ .

### 74 3.1 Step 1: Finding an $X'$ in $\mathbb{X}_S$ that minimizes $d_K(X, X')$

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

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

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

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

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

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

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

88 The intuition behind choosing these specific weights and  $\varepsilon(X, S)$  being a lower bound is as follows.  
 89 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  
 90 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  
 91 have to take into additional account is increased by  $F_X(\hat{x}_{i+1}) - F_X(x_i) = P(x_i < X < x_{i+1})$ .

92 Formally we have the following.

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

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

97 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  
 98  $d_k(X, X') \geq |F_X(\hat{x}_{i+1})| = |F_X(\hat{x}_{i+1}) - F_X(x_i)| = P(x_i < X < x_{i+1}) = w(x_i, x_{i+1})$ .

99 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  
100  $d_k(X, X') \geq |1 - F_X(\hat{x}_i)| = |F_X(\hat{x}_{i+1}) - F_X(x_i)| = P(x_i < X < x_{i+1}) = w(x_i, x_{i+1})$ .

101 Otherwise for every  $1 \leq i < m$ , we use the fact that  $\max\{|a|, |b|\} \geq |a - b|/2$  for every  $a, b \in$   
102  $\mathbb{R}$ , 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  $d_k(X, X') \geq$   
103  $1/2|F_X(\hat{x}_{i+1}) - F_X(x_i)| = P(x_1 < X < x_2)/2 = w(x_i, x_{i+1})$ .

104 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  
105 follows.  $\square$

106 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  
107  $m$ -approximation among the set  $\mathbb{X}_S$ . We define  $X'$  as follows:

108 **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  $f_{X'}(x) = 0$   
109 for  $x \notin S$ .

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

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

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

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

120 **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  $-w(x_i, x_{i+1}) \leq$   
121  $F_X(x) - F_{X'}(x) \leq w(x_i, x_{i+1})$ .

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

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

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

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

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

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

138 **Corrolary 9.**  $d_k(X, X') = \varepsilon(X, S)$ .

### 139 3.2 Step 2: Finding an $S$ that minimizes $\varepsilon(X, S)$

140 Chakravarty, Orlin, and Rothblum [2] proposed a polynomial-time method that, given a certain  
 141 objective functions (additive), finds an optimal consecutive partition. Their method involves the  
 142 construction of a graph such that the (consecutive) set partitioning problem is reduced to the problem  
 143 of finding the shortest path in that graph.

144 The KolmogorovApprox algorithm (Algorithm 1) starts by constructing a directed weighted graph  
 145  $G$  similar to the method of Chakravarty, Orlin, and Rothblum [2]. The nodes  $V$  consist of the  
 146 support of  $X$  together with an extra two nodes,  $-\infty$  and  $\infty$  for technical reasons, whereas the  
 147 edges  $E$  connect every pair of nodes in one direction (lines 1-2). The weight  $w$  of each edge  
 148  $e = (x, y) \in E$  is determined by one of two cases as in Definition 3. The first is where nodes  
 149  $x$  or  $y$  are the source or target nodes respectively. In this case, the weight is the probability of  $X$   
 150 to get a value between  $x$  and  $y$ , non inclusive, i.e.,  $w(e) = \Pr(x < X < y)$ . The second case  
 151 is where  $x$  and  $y$  are not a source or target nodes, here the weight is the probability of  $X$  to get a  
 152 value between  $x$  and  $y$ , non inclusive, divided by two i.e.,  $w(e) = \Pr(x < X < y)/2$ . The values  
 153 taken are non inclusive, since we are interested only in the error value. The source node of the  
 154 shortest path problem at hand corresponds to the  $-\infty$  node added to  $G$  in the construction phase,  
 155 and the target node is the extra node  $\infty$ . The set of all solution paths in  $G$ , i.e., those starting at  
 156  $-\infty$  and ending in  $\infty$  with at most  $m$  edges, is called  $paths(G, -\infty, \infty)$ . The goal is to find the  
 157 path  $l$  in  $paths(G, -\infty, \infty)$  with the lightest bottleneck (line 3). This can be achieved by using the  
 158 *Bellman – Ford* algorithm with two tweaks. The first is to iterate the graph  $G$  in order to find only  
 159 paths with length of at most  $m$  edges. The second is to find the lightest bottleneck as opposed to  
 160 the traditional objective of finding the shortest path. This is performed by modifying the manner of  
 161 “relaxation” to  $bottleneck(x) = \min[\max(bottleneck(v), w(e))]$ , done also in [14]. Consequently,  
 162 we find the lightest maximal edge in a path of length  $\leq m$ , which represents the minimal error,  
 163  $\varepsilon(X, S)$ , defined in Definition ?? where the nodes in path  $l$  represent the elements in set  $S$ . The  
 164 approximated random variable  $X'$  is then derived from the resulting path  $l$  (lines 4-5). Every node  
 165  $x \in l$  represent a value in the new calculated random variable  $X'$ , we than iterate the path  $l$  to find  
 166 the probability of the event  $f_{X'}(x)$  as described in Definition 6. For every edge  $(x_i, x_j) \in l$  we  
 167 determine: if  $(x_i, x_j)$  is the first edge in the path  $l$  (i.e.  $x_i = -\infty$ ), then node  $x_j$  gets the full weight  
 168  $w(x_i, x_j)$  and it's own weight in  $X$  such that  $f_{X'}(x_j) = f_X(x_j) + w(x_i, x_j)$ . If  $(x_i, x_j)$  in not the  
 169 first nor the last edge in path  $l$  then we divide it's weight between nodes  $x_i$  and  $x_j$  in addition to their  
 170 own original weight in  $X$  and the probability that already accumulated. If  $(x_i, x_j)$  is the last edge  
 171 in the path  $l$  (i.e.  $i = \infty$ ) then node  $i$  gets the full weight  $w(x_i, x_j)$  in addition to what was already  
 172 accumulated such that  $f_{X'}(x_j) = f_{X'}(x_i) + w(x_i, x_j)$ .

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**Algorithm 1:** KolmogorovApprox( $X, m$ )

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1  $S = \text{support}(X) \cup \{\infty, -\infty\}$ 
2  $G = (V, E) = (S, \{(x, y) : x < y\})$ 
3  $(x_0, \dots, x_{m+1}) = l \in \text{argmin}_{l \in paths(G, -\infty, \infty), |l| \leq m} \max\{w(e) : e \in l\}$ 
4 for  $0 < i < m + 1$  do
5    $f_{X'}(x_i) = w(x_{i-1}, x_i) + w(x_i, x_{i+1}) + f_X(x_i)$ 
6 return  $X'$ 

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173 **Theorem 10.** KolmogorovApprox( $X, m$ ) is an  $m$ -optimal-approximation of  $X$ .

174 *Proof.* If we consider the vertexes  $S = l \setminus \{-\infty, \infty\}$  for a path  $l \in \text{paths}(G, -\infty, \infty)$  we have  
 175 that  $\max\{w(e) : e \in l\} = \varepsilon(X, S)$ . Therefore, line 3 of the algorithm essentially computes a set  
 176  $S \in \arg\min_{S \subseteq \text{support}(X), |S| \leq m} \varepsilon(X, S)$ . By Corollary 9, the variable  $X'$  constructed in lines 4 and  
 177 5 satisfies  $d_K(X, X') = \varepsilon(X, S)$  and by the minimality of  $S$  and by Proposition 5, it is an optimal  
 178 approximation.  $\square$

179 **Theorem 11.** *The KolmogorovApprox( $X, m$ ) algorithm runs in time  $O(mn^2)$ , using  $O(n^2)$  mem-*  
 180 *ory where  $n = |\text{support}(X)|$ .*

181 *Proof.* Constructing the graph  $G$  takes  $O(n^2)$ . The number of edges is  $O(E) \approx O(n^2)$  and for every  
 182 edge the weight is at most the sum of all probabilities between the source node  $-\infty$  and the target  
 183 node  $\infty$ , which can be done efficiently by aggregating the weights of already calculated edges. The  
 184 construction is also the only stage that requires memory allocation, specifically  $O(E + V) = O(n^2)$ .  
 185 Finding the shortest path takes  $O(m(E + V)) \approx O(mn^2)$ .

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

187 Since  $G$  is DAG (directed acyclic graph) finding shortest path takes  $O(E + V)$ . We only need  
 188 to find paths of length  $\leq m$ , which takes  $O(m(E + V))$ . Deriving the new random variable  $X'$   
 189 from the computed path  $l$  takes  $O(mn)$ . For every node in  $l$  (at most  $m$  nodes), calculating the  
 190 probability  $P(s < X < \infty)$  takes at most  $n$  steps. To conclude, the worst case run-time complexity  
 191 is  $O(n^2 + mn^2 + mn) = O(mn^2)$  and memory complexity is  $O(E + V) = O(n^2)$ .  $\square$

## 192 4 A case study and experimental results

193 The case study examined in our experiments is the problem of task trees with deadlines [4, 3].  
 194 Hierarchical planning is a well-established field in AI [5, 6, 7], and is still relevant nowadays [1, 15].  
 195 A hierarchical plan is a method for representing problems of automated planning in which the  
 196 dependency among tasks can be given in the form of networks, here we focus on hierarchical plans  
 197 represented by task trees. The leaves in a task tree are *primitive* actions (or tasks), and the internal  
 198 nodes are either *sequence* or *parallel* actions. The plans we deal with are of stochastic nature, where  
 199 the duration of a primitive action is given by a random variable.

200 A sequence node denotes a series of tasks that should be performed consecutively, whereas a parallel  
 201 node denotes a set of tasks that begin at the same time. A *valid* plan is one that is fulfilled before some  
 202 given *deadline*, i.e., its *makespan* is less than or equal to the deadline. The objective in this context  
 203 is to compute the probability that a given plan is valid, or more formally computing  $P(X < T)$ ,  
 204 where  $X$  is a random variable representing the makespan of the plan and  $T$  is the deadline. As said  
 205 above, resource consumption (task duration) is uncertain, and described as probability distributions  
 206 in the leaf nodes. We assume that the distributions are independent but *not* necessarily identically  
 207 distributed and that the random variables are discrete and have a finite support.

208 The problem of finding the probability that a task tree satisfies a deadline is known to be NP-hard. In  
 209 fact, even the problem of summing a set of random variables is NP-hard [10]. This is an example of  
 210 an explicitly given random variable that we need to estimate deadline meeting probabilities for.

211 In the first experiment we focus on is the problem of task trees with deadlines, and consider three  
 212 types of task trees. The first type includes logistic problems of transporting packages by trucks and  
 213 airplanes (from IPC2 <http://ipc.icaps-conference.org/>). Hierarchical plans of those logistic problems  
 214 were generated by the JSHOP2 planner [11] (see example problem, Figure 1, one parallel node with  
 215 all descendant task nodes being in sequence). The second type consists of task trees used as execution

plans for the ROBIL team entry in the DARPA robotics challenge (DRC simulation phase), and the third type is of linear plans (sequential task trees). The primitive tasks in all the trees are modeled as discrete random variables with support of size  $M$  obtained by discretization of uniform distributions over various intervals. The number of tasks in a tree is denoted by  $N$ .

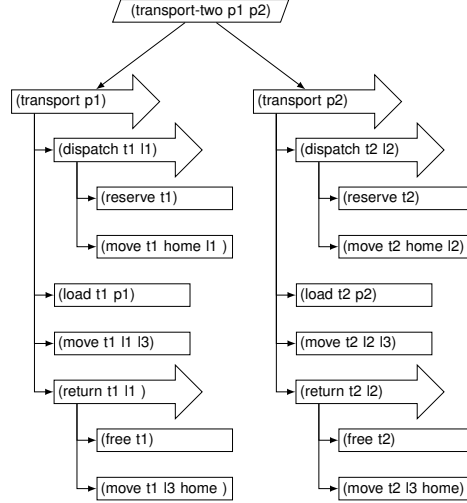


Figure 1: A plan generated by the JSHOP2 algorithm. Arrow shapes represent sequence nodes, parallelograms represent parallel nodes, and rectangles represent primitive nodes.

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 [3] and the Trim [4] 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  $\varepsilon$  given to the Trim operator. Note that in order to obtain some error  $\varepsilon$ , 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	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	0
	4	0	0.024	0.04	0.008	0.0016
	10	0	0.028	0.06	0.0117	0.001

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

Table 1 shows the results of the main experiment. The quality of the solutions provided by using the OptTrim operator are better (lower errors) than those provided by the Trim operator, 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 OptTrim. 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 from a uniform distribution and then normalizing these probabilities so that they sum to one.

Figure ?? 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, safe to say, a half of the error produced by OptTrim and Trim, it is clear both in the table (the relative error is mostly above 1) and in the graph.

We also examined how our algorithm compares to linear programming as described and discussed, for example, in [12]. 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 “Minimize” function of Wolfram Mathematica and fed it with the equations  $\min_{\alpha \in \mathbb{R}^n} \|x - \alpha\|_\infty$  subject to  $\|\alpha\|_0 \leq m$  and  $\|\alpha\|_1 = 1$ . The run-time comparison results were clear and persuasive, for a random variable with support size  $n = 10$  and  $m = 5$ , the LP algorithm run-time was 850 seconds, where the KolmogorovApprox algorithm run-time was less than a tenth of a second. For  $n = 100$  and  $m = 5$ , the KolmogorovApprox algorithm run-time was 0.14 seconds and the LP algorithm took more than a day. Due to these timing results of the LP algorithm we did not proceed to examine it any further. Since it is not trivial to formally analyze the run-time of the LP algorithm, we conclude by the reported experiment that in this case the LP algorithm might not be as efficient as KolmogorovApprox algorithm whose complexity is proven to be polynomial in Theorem 11.

## 5 Discussion

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