

A Kernel for Hierarchical Parameter Spaces

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February 23, 2014

Abstract

We define a family of kernels for mixed continuous/discrete hierarchical parameter spaces and show that they are positive definite.

1 Introduction

We aim to do inference about some function g with domain (input space) \mathcal{X} . $\mathcal{X} = \prod_{i=1}^D \mathcal{X}_i$ is a D -dimensional input space, where each individual dimension is either bounded real or categorical, that is, \mathcal{X}_i is either $[l_i, u_i] \subset \mathbb{R}$ (with lower and upper bounds l_i and u_i , respectively) or $\{v_{i,1}, \dots, v_{i,m_i}\}$.

Associated with \mathcal{X} , there is a DAG structure \mathcal{D} , whose vertices are the dimensions $\{1, \dots, D\}$. \mathcal{X} will be restricted by \mathcal{D} : if vertex i has children under \mathcal{D} , \mathcal{X}_i must be categorical. \mathcal{D} is also used to specify when each input is *active* (that is, relevant to inference about g). In particular, we assume each input dimension is only active under some instantiations of its ancestor dimensions in \mathcal{D} . More precisely, we define D functions $\delta_i: \mathcal{X} \rightarrow \mathcal{B}$, for $i \in \{1, \dots, D\}$, and where $\mathcal{B} = \{\text{true}, \text{false}\}$. We take

$$\delta_i(\underline{x}) = \delta_i(\underline{x}(\text{anc}_i)), \quad (1)$$

where anc_i are the ancestor vertices of i in \mathcal{D} , such that $\delta_i(\underline{x})$ is true only for appropriate values of those entries of \underline{x} corresponding to ancestors of i in \mathcal{D} . We say i is active for \underline{x} iff $\delta_i(\underline{x})$.

Our aim is to specify a kernel for \mathcal{X} , *i.e.*, a positive semi-definite function $k: \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}$. We will first specify an individual kernel for each input dimension, *i.e.*, a positive semi-definite function $k_i: \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}$. k can then be taken as either a sum,

$$k(\underline{x}, \underline{x}') = \sum_{i=1}^D k_i(\underline{x}, \underline{x}'), \quad (2)$$

product,

$$k(\underline{x}, \underline{x}') = \prod_{i=1}^D k_i(\underline{x}, \underline{x}'), \quad (3)$$

or any other permitted combination, of these individual kernels. Note that each individual kernel k_i will depend on an input vector \underline{x} only through dependence on x_i and $\delta_i(\underline{x})$,

$$k_i(\underline{x}, \underline{x}') = \tilde{k}_i(x_i, \delta_i(\underline{x}), x'_i, \delta_i(\underline{x}')). \quad (4)$$

That is, x_j for $j \neq i$ will influence $k_i(\underline{x}, \underline{x}')$ only if $j \in \text{anc}_i$, and only by affecting whether i is active.

Below we will construct pseudometrics $d_i: \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}^+$: that is, d_i satisfies the requirements of a metric aside from the identity of indiscernibles. As for k_i , these pseudometrics will depend on an input vector \underline{x} only through dependence on both x_i and $\delta_i(\underline{x})$. $d_i(\underline{x}, \underline{x}')$ will be designed to provide an intuitive measure of how different $g(\underline{x})$ is from $g(\underline{x}')$. For each i , we will then construct a (pseudo-)isometry f_i from \mathcal{X} to a Euclidean space (\mathbb{R}^2 for bounded real parameters, and \mathbb{R}^m for categorical-valued parameters with m choices). That is, denoting the Euclidean metric on the appropriate space as d_E , f_i will be such that

$$d_i(\underline{x}, \underline{x}') = d_E(f_i(\underline{x}), f_i(\underline{x}')) \quad (5)$$

for all $\underline{x}, \underline{x}' \in \mathcal{X}$. We can then use our transformed inputs, $f_i(\underline{x})$, within any standard Euclidean kernel κ . We'll make this explicit in Proposition 2.

Definition 1. A function $\kappa: \mathbb{R}^+ \rightarrow \mathbb{R}$ is a positive semi-definite covariance function over Euclidean space if $K \in \mathbb{R}^{N \times N}$, defined by

$$K_{m,n} = \kappa(d_E(y_m, y_n)), \quad \text{for } y_m, y_n \in \mathbb{R}^P, \quad m, n = 1, \dots, N,$$

is positive semi-definite for any $y_1, \dots, y_N \in \mathbb{R}^P$.

A popular example of such a κ is the exponentiated quadratic, for which $\kappa(\delta) = \sigma^2 \exp(-\frac{1}{2} \frac{\delta^2}{\lambda^2})$; another popular choice is the rational quadratic, for which $\kappa(\delta) = \sigma^2 (1 + \frac{1}{2\alpha} \frac{\delta^2}{\lambda^2})^{-\alpha}$.

Proposition 2. Let κ be a positive semi-definite covariance function over Euclidean space and let d_i satisfy Equation 5. Then, $k_i: \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}^+$, defined by

$$k_i(\underline{x}, \underline{x}') = \kappa(d_i(\underline{x}, \underline{x}'))$$

is a positive semi-definite covariance function over input space \mathcal{X} .

Proof. We need to show that for any $\underline{x}_1, \dots, \underline{x}_N \in \mathcal{X}$, $K \in \mathbb{R}^{N \times N}$ defined by

$$K_{m,n} = \kappa(d_i(\underline{x}_m, \underline{x}_n)), \quad \text{for } \underline{x}_m, \underline{x}_n \in \mathcal{X}, \quad m, n = 1, \dots, N,$$

is positive semi-definite. Now, by the definition of d_i ,

$$K_{m,n} = \kappa(d_E(f_i(\underline{x}_m), f_i(\underline{x}_n))) = \kappa(d_E(y_m, y_n))$$

where $y_m = f_i(\underline{x}_m)$ and $y_n = f_i(\underline{x}_n)$ are elements of \mathbb{R}^P . Then, by assumption that κ is a positive semi-definite covariance function over Euclidean space, K is positive semi-definite. \square

We'll now define pseudometrics d_i and associated isometries f_i for both the bounded real and categorical cases.

2 Bounded Real Dimensions

Let's first focus on a bounded real input dimension i , i.e., $\mathcal{X}_i = [l_i, u_i]$. To emphasize that we're in this real case, we explicitly denote the pseudometric as d_i^r and the (pseudo-)isometry from (\mathcal{X}, d_i) to \mathbb{R}^2, d_E as f_i^r . For the definitions, recall that $\delta_i(\underline{x})$ is true iff dimension i is active given the instantiation of i 's ancestors in \underline{x} .

$$d_i^r(\underline{x}, \underline{x}') = \begin{cases} 0 & \text{if } \delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{false} \\ \omega_i & \text{if } \delta_i(\underline{x}) \neq \delta_i(\underline{x}') \\ \omega_i \sqrt{2} \sqrt{1 - \cos(\pi \rho_i \frac{x_i - x'_i}{u_i - l_i})} & \text{if } \delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{true}. \end{cases}$$

$$f_i^r(\underline{x}) = \begin{cases} [0, 0]^\top & \text{if } \delta_i(\underline{x}) = \text{false} \\ \omega_i [\sin \pi \rho_i \frac{x_i - l_i}{u_i - l_i}, \cos \pi \rho_i \frac{x_i - l_i}{u_i - l_i}]^\top & \text{otherwise.} \end{cases}.$$

Although our formal arguments do not rely on this, Proposition 5 in the appendix shows that d_i^r is a pseudometric. This pseudometric is defined by two parameters: $\omega_i \in [0, 1]$ and $\rho_i \in [0, 1]$. We firstly define

$$\omega_i = \prod_{j \in \text{anc}_i \cup \{i\}} \gamma_j, \quad (6)$$

where $\gamma_j \in [0, 1]$. This encodes the intuitive notion that differences on lower levels of the hierarchy count less than differences in their ancestors.

Also note that, as desired, if i is inactive for both \underline{x} and \underline{x}' , d_i^r specifies that $g(\underline{x})$ and $g(\underline{x}')$ should not differ owing to differences between x_i and x'_i . Secondly, if i is active for both \underline{x} and \underline{x}' , the difference between $g(\underline{x})$ and $g(\underline{x}')$ due to x_i and x'_i increases monotonically with increasing $|x_i - x'_i|$. Parameter ρ_i controls whether differing in the activity of i contributes more or less to the distance than differing in x_i should i be active. If $\rho = 1/3$, and if i is inactive for exactly one of \underline{x} and \underline{x}' , $g(\underline{x})$ and $g(\underline{x}')$ are as different as is possible due to dimension i ; that is, $g(\underline{x})$ and $g(\underline{x}')$ are exactly as different in that case as if $x_i = l_i$ and $x'_i = u_i$. For $\rho > 1/3$, i being active for both \underline{x} and \underline{x}' means that $g(\underline{x})$ and $g(\underline{x}')$ could potentially be more different than if i was active in only one of them. For $\rho < 1/3$, the converse is true.¹

We now show that d_i^r and f_i^r can be plugged into a positive semi-definite kernel over Euclidean space to define a valid kernel over space \mathcal{X} .

Proposition 3. *Let κ be a positive semi-definite covariance function over Euclidean space. Then, $k_i: \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}^+$, defined by*

$$k_i(\underline{x}, \underline{x}') = \kappa(d_i^r(\underline{x}, \underline{x}'))$$

is a positive semi-definite covariance function over input space \mathcal{X} .

¹Note that \underline{x} and \underline{x}' must differ in at least one ancestor dimension of i in order for $\delta_i(\underline{x}) \neq \delta_i(\underline{x}')$ to hold, such that in the final kernel combining kernels k_i due to each dimension i , differences in the activity of dimension i are penalized both in kernel k_i and in the distance for the kernel of the ancestor dimension causing the difference in i 's activity.

Proof. Due to Proposition 2, we only need to show that, for any two inputs $\underline{x}, \underline{x}' \in \mathcal{X}$, the isometry condition $d_E(f_i^r(\underline{x}), f_i^r(\underline{x}')) = d_i^r(\underline{x}, \underline{x}')$ holds.

We use the abbreviation $\alpha = \pi \rho_i \frac{x_i}{u_i - l_i}$ and $\alpha' = \pi \rho_i \frac{x'_i}{u_i - l_i}$ and consider the following three possible cases of dimension i being active or inactive in \underline{x} and \underline{x}' .

Case 1: $\delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{false}$. In this case, we trivially have

$$d_E(f_i^r(\underline{x}), f_i^r(\underline{x}')) = d_E([0, 0]^\top, [0, 0]^\top) = 0 = d_i^r(\underline{x}, \underline{x}').$$

Case 2: $\delta_i(\underline{x}) \neq \delta_i(\underline{x}')$. In this case, we have

$$d_E(f_i^r(\underline{x}), f_i^r(\underline{x}')) = d_E([\sin \alpha, \cos \alpha]^\top, [0, 0]^\top) = \sqrt{\omega_i^2(\sin^2 \alpha + \cos^2 \alpha)} = \omega_i = d_i^r(\underline{x}, \underline{x}'),$$

and symmetrically for $d_E([0, 0]^\top, [\sin \alpha, \cos \alpha]^\top)$.

Case 3: $\delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{true}$. We have:

$$\begin{aligned} d_E(f_i^r(\underline{x}), f_i^r(\underline{x}')) &= d_E(\omega_i[\sin \alpha, \cos \alpha]^\top, \omega_i[\sin \alpha', \cos \alpha']^\top) \\ &= \omega_i \sqrt{(\sin \alpha - \sin \alpha')^2 + (\cos \alpha - \cos \alpha')^2} \\ &= \omega_i \sqrt{\sin^2 \alpha - 2 \sin \alpha \sin \alpha' + \sin^2 \alpha' + \cos^2 \alpha - 2 \cos \alpha \cos \alpha' + \cos^2 \alpha'} \\ &= \omega_i \sqrt{(\sin^2 \alpha + \cos^2 \alpha) + (\sin^2 \alpha' + \cos^2 \alpha') - 2(\sin \alpha \sin \alpha' + \cos \alpha \cos \alpha')} \\ &= \omega_i \sqrt{1 + 1 - 2 \cos(\alpha - \alpha')} \\ &= \omega_i \sqrt{2} \sqrt{1 - \cos(\pi \rho_i \frac{x_i - x'_i}{u_i - l_i})} = d_i^r(\underline{x}, \underline{x}'), \end{aligned} \tag{7}$$

where (7) follows from the previous line by using the identity

$$\cos(a - b) = \cos a \cos b + \sin a \sin b.$$

□

3 Categorical Dimensions

Now let's define f_i^c and d_i^c for the case that the input $\mathcal{X}_i = \{v_{i,1}, \dots, v_{i,m_i}\}$ is categorical with m_i possible values. Proceeding as above, we define a pseudometric d_i^c on \mathcal{X} and an isometry from (\mathcal{X}, d_i^c) to $(\mathbb{R}^{m_i}, d_E^{m_i})$, and show that we can combine these with a kernel over Euclidean space to construct a valid kernel over space \mathcal{X} .

$$d_i^c(\underline{x}, \underline{x}') = \begin{cases} 0 & \text{if } \delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{false} \\ \omega_i & \text{if } \delta_i(\underline{x}) \neq \delta_i(\underline{x}') \\ \omega_i \frac{\sqrt{2}\rho}{1+(m_i-1)(1-\rho)^2} \mathbb{I}_{x_i \neq x'_i} & \text{if } \delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{true}. \end{cases}$$

$$f_i^c(\underline{x}) = \begin{cases} \underline{0} \in \mathbb{R}^{m_i} & \text{if } \delta_i(\underline{x}) = \text{false} \\ \omega_i \frac{e_j + (1-\rho) \sum_{l \neq j} e_l}{\sqrt{1 + (m_i - 1)(1-\rho)^2}} & \text{if } \delta_i(\underline{x}) = \text{true and } x_i = v_{i,j}, \end{cases}$$

where $e_j \in \mathbb{R}^{m_i}$ is the j th unit vector: zero in all dimensions except j , where it is 1. Note that

$$\sqrt{1 + (m_i - 1)(1-\rho)^2} = \left\| e_j + (1-\rho) \sum_{l \neq j} e_l \right\|. \quad (8)$$

Again, although our analysis does not require it, we prove in Proposition 6 (see appendix) that d_i^c is a pseudometric. Our pseudometric is again defined by two hyperparameters. Firstly, $\omega_i \in [0, 1]$ is exactly as defined in (6), and similarly allows higher-level inputs to attain greater importance. Similarly, $\rho_i \in [0, 1]$ allows control of to what extent differing in the activity of i affects the distance relative to the influence of differing in x_i should i be active. In particular, for

$$\rho_i^* = \frac{\sqrt{2} - 2 + 2m_i - \sqrt{6 - 4\sqrt{2} + 4(\sqrt{2} - 1)m_i}}{2(m_i - 1)}, \quad (9)$$

$\rho_i < \rho_i^*$ implies that differing in the activity of i is more significant, whereas $\rho_i > \rho_i^*$ implies the converse. The special case $\rho = 0$ dictates that differing in x_i has no influence on the distance; $\rho = 1$ assigns maximal importance to differing in x_i .

Proposition 4. *Let κ be a positive semi-definite covariance function over Euclidean space. Then, $k_i: \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}^+$, defined by*

$$k_i(\underline{x}, \underline{x}') = \kappa(d_i^c(\underline{x}, \underline{x}'))$$

is a positive semi-definite covariance function over input space \mathcal{X} .

Proof. We proceed as in the proof of Proposition 3 to show that, for any two inputs $\underline{x}, \underline{x}' \in \mathcal{X}$, the isometry condition $d_E^{m_i}(f_i^c(\underline{x}), f_i^c(\underline{x}')) = d_i^c(\underline{x}, \underline{x}')$ holds.

Case 1: $\delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{false}$. In this case, we trivially have

$$d_E^{m_i}(f_i^c(\underline{x}), f_i^c(\underline{x}')) = d_E^{m_i}(\underline{0}, \underline{0}) = 0 = d_i^c(\underline{x}, \underline{x}').$$

Case 2: $\delta_i(\underline{x}) \neq \delta_i(\underline{x}')$. In this case, we have

$$d_E^{m_i}(f_i^c(\underline{x}), f_i^c(\underline{x}')) = d_E^{m_i}\left(\omega_i \frac{e_j + (1-\rho) \sum_{l \neq j} e_l}{\|e_j + (1-\rho) \sum_{l \neq j} e_l\|}, \underline{0}\right) = \omega_i = d_i(\underline{x}, \underline{x}'),$$

and symmetrically for $d_E\left(\underline{0}, \omega_i \frac{e_j + (1-\rho) \sum_{l \neq j} e_l}{\|e_j + (1-\rho) \sum_{l \neq j} e_l\|}\right)$.

Case 3: $\delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{true}$. If $x_i = x'_i = v_{i,j}$, we have

$$d_E^{m_i}(f_i^c(\underline{x}), f_i^c(\underline{x}')) = d_E^{m_i}(f_i^c(\underline{x}), f_i^c(\underline{x})) = 0 = d_i^c(\underline{x}, \underline{x}').$$

If $x_i = v_{i,j} \neq v_{i,j'} = x'_i$, we have

$$\begin{aligned}
d_E(f_i^c(\underline{x}), f_i^c(\underline{x}')) &= d_E^{m_i} \left(\omega_i \frac{e_j + (1-\rho) \sum_{l \neq j} e_l}{\sqrt{1 + (m_i - 1)(1-\rho)^2}}, \omega_i \frac{e'_j + (1-\rho) \sum_{l \neq j'} e_l}{\sqrt{1 + (m_i - 1)(1-\rho)^2}} \right) \\
&= \omega_i \frac{\sqrt{(1 - (1-\rho))^2 + (1 - (1-\rho))^2}}{1 + (m_i - 1)(1-\rho)^2} \\
&= \omega_i \frac{\sqrt{2}\rho}{1 + (m_i - 1)(1-\rho)^2} \\
&= d_i^c(\underline{x}, \underline{x}').
\end{aligned} \tag{10}$$

□

A Proof of pseudometric properties

Proposition 5. d_i^r is a pseudometric on \mathcal{X} .

Proof. The non-negativity and symmetry of d_i^r are trivially proven. To prove the triangle inequality, consider $\underline{x}, \underline{x}', \underline{x}'' \in \mathcal{X}$.

Case 1: $\delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{false}$, such that $d_i^r(\underline{x}, \underline{x}') = 0$. Here, from non-negativity, clearly $d_i^r(\underline{x}, \underline{x}') = 0 \leq d_i^r(\underline{x}, \underline{x}'') + d_i^r(\underline{x}', \underline{x}'')$.

Case 2: $\delta_i(\underline{x}) \neq \delta_i(\underline{x}')$, such that $d_i^r(\underline{x}, \underline{x}') = \omega_i$. Without loss of generality, assume $\delta_i(\underline{x}) = \text{true}$, $\delta_i(\underline{x}') = \text{false}$ and $\delta_i(\underline{x}'') = \text{true}$.

$$d_i^r(\underline{x}, \underline{x}'') + d_i^r(\underline{x}', \underline{x}'') = d_i^r(\underline{x}, \underline{x}'') + \omega_i \tag{11}$$

Hence $d_i^r(\underline{x}, \underline{x}'') + d_i^r(\underline{x}', \underline{x}'') \geq \omega_i = d_i^r(\underline{x}, \underline{x}')$ by non-negativity.

Case 3: $\delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{true}$, such that $d_i^r(\underline{x}, \underline{x}') = \omega_i \sqrt{2} \sqrt{1 - \cos(\pi \rho_i \frac{x_i - x'_i}{u_i - l_i})}$. If $\delta_i(\underline{x}'') = \text{false}$,

$$d_i^r(\underline{x}, \underline{x}'') + d_i^r(\underline{x}', \underline{x}'') = 2\omega_i \geq \omega_i \sqrt{2} \sqrt{1 - \cos(\pi \rho_i \frac{x_i - x'_i}{u_i - l_i})} = d_i^r(\underline{x}, \underline{x}'). \tag{12}$$

If $\delta_i(\underline{x}'') = \text{true}$, consider the ‘worst’ possible case in which, without loss of generality, $x_i = l_i$ and $x'_i = u_i$, such that $d_i^r(\underline{x}, \underline{x}') = 2\omega_i^2$. We define the abbreviation $\beta'' =$

$\frac{x'' - l_i}{u_i - l_i}$, giving

$$\begin{aligned}
(d_i^r(\underline{x}, \underline{x}'') + d_i^r(\underline{x}', \underline{x}''))^2 &= 2\omega_i^2 \left(\sqrt{1 - \cos(\pi\rho_i\beta'')} + \sqrt{1 - \cos(\pi\rho_i(1 - \beta''))} \right)^2 \\
&= 2\omega_i^2 \left(2 - \cos(\pi\rho_i\beta'') - \cos(\pi\rho_i(1 - \beta'')) \right. \\
&\quad \left. + 2\sqrt{(1 - \cos(\pi\rho_i\beta''))(1 - \cos(\pi\rho_i(1 - \beta'')))} \right) \\
&= 2\omega_i^2 \left(2 + 2\sqrt{1 + \cos(\pi\rho_i\beta'')\cos(\pi\rho_i(1 - \beta''))} \right) \\
&= 4\omega_i^2 (1 + |\sin \pi\rho_i\beta''|) \\
&\geq 4\omega_i^2 = d_i^r(\underline{x}, \underline{x}')^2.
\end{aligned} \tag{13}$$

Hence, from non-negativity, we have $d_i^r(\underline{x}, \underline{x}'') + d_i^r(\underline{x}', \underline{x}'') \geq d_i^r(\underline{x}, \underline{x}')$. \square

Proposition 6. d_i^c is a pseudometric on \mathcal{X} .

Proof. The non-negativity and symmetry of d_i^c are trivially proven. To prove the triangle inequality, consider $\underline{x}, \underline{x}', \underline{x}'' \in \mathcal{X}$.

Case 1: $\delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{false}$, such that $d_i^c(\underline{x}, \underline{x}') = 0$. Here, from non-negativity, clearly $d_i^c(\underline{x}, \underline{x}') = 0 \leq d_i^c(\underline{x}, \underline{x}'') + d_i^c(\underline{x}', \underline{x}'')$.

Case 2: $\delta_i(\underline{x}) \neq \delta_i(\underline{x}')$, such that $d_i^c(\underline{x}, \underline{x}') = \omega_i$. Without loss of generality, assume $\delta_i(\underline{x}) = \text{true}$, $\delta_i(\underline{x}') = \text{false}$ and $\delta_i(\underline{x}'') = \text{true}$.

$$d_i^c(\underline{x}, \underline{x}'') + d_i^c(\underline{x}', \underline{x}'') = d_i^c(\underline{x}, \underline{x}'') + \omega_i \tag{14}$$

Hence $d_i^c(\underline{x}, \underline{x}'') + d_i^c(\underline{x}', \underline{x}'') \geq \omega_i = d_i^c(\underline{x}, \underline{x}')$ by non-negativity.

Case 3: $\delta_i(\underline{x}) = \delta_i(\underline{x}') = \text{true}$, such that $d_i^c(\underline{x}, \underline{x}') = \omega_i \frac{\sqrt{2}\rho}{1 + (m_i - 1)(1 - \rho)^2} \mathbb{I}_{x_i \neq x'_i}$. If $\delta_i(\underline{x}'') = \text{false}$,

$$d_i^c(\underline{x}, \underline{x}'') + d_i^c(\underline{x}', \underline{x}'') = 2\omega_i \geq \omega_i \frac{\sqrt{2}\rho}{1 + (m_i - 1)(1 - \rho)^2} \mathbb{I}_{x_i \neq x'_i} = d_i^c(\underline{x}, \underline{x}'). \tag{15}$$

If $\delta_i(\underline{x}'') = \text{true}$,

$$\begin{aligned}
d_i^c(\underline{x}, \underline{x}'') + d_i^c(\underline{x}', \underline{x}'') &= \omega_i \frac{\sqrt{2}\rho}{1 + (m_i - 1)(1 - \rho)^2} (\mathbb{I}_{x_i \neq x''_i} + \mathbb{I}_{x'_i \neq x''_i}) \\
&\geq \omega_i \frac{\sqrt{2}\rho}{1 + (m_i - 1)(1 - \rho)^2} \mathbb{I}_{x_i \neq x'_i} = d_i^c(\underline{x}, \underline{x}').
\end{aligned} \tag{16}$$

\square