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Approximation and Parameterized Algorithms for Segment Set Cover

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6

Master's thesis

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in **COMPUTER SCIENCE**

8

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9

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10 **Supervisor's statement**

11 Hereby I confirm that the presented thesis was prepared under my supervision and
12 that it fulfils the requirements for the degree of Master of Computer Science.

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15 Hereby I declare that the presented thesis was prepared by me and none of its contents
16 was obtained by means that are against the law.

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18 degree.

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20 electronic version.

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Abstract

23 The work presents a study of different geometric set cover problems. It mostly focuses on
24 segment set cover and its connection to the polygon set cover.

25

Keywords

26 set cover, geometric set cover, FPT, $W[1]$ -completeness, APX-completeness, PCP theorem,
27 NP-completeness

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36 Algorytmy aproksymacyjne i parametryzowane dla problemu pokrywania punktów
37 odcinkami na płaszczyźnie

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Chapter 1

Introduction

Some problems in Computer Science are known to be NP-complete, meaning that assuming $P \neq NP$ there is no polynomial time algorithm that can solve these problems. Even so, they still can be amenable to different approaches, such as approximation or parametrization.

Definition 1.1. In the **Set Cover** problem we are given a set of elements (universe) \mathcal{C} and a family of sets \mathcal{P} , that are subsets of the universe \mathcal{C} and sum up to the whole \mathcal{C} . Our task is to find such a set $\mathcal{R} \subseteq \mathcal{P}$, that $\bigcup \mathcal{R} = \mathcal{C}$ and size of \mathcal{R} is minimal possible.

Set Cover is one classical example of an NP-complete problem, which has been proven in literature to be inapproximable with factor $(1 - o(1)) \ln n$ unless $P = NP$ (which is a stronger result than APX-hardness), and W[2]-hard with natural parametrization, but restricting the problem to various specialized settings can lead to more tractable special cases. In this thesis we take a closer look at the Geometric Set Cover problem in the plane, where points to cover are points in the plane and sets to cover them with are geometric objects.

Approximation Over the years there has been a lot of work related to approximation of Geometric Set Cover. Notably, Geometric Set Cover with unweighted unit disks admits a PTAS (see Corollary 1.1 in [Mustafa and Ray, 2010]). When we consider the same problem with weighted unit disks (or unit squares), the problem admits a QPTAS [Mustafa et al., 2014], see also [Pilipczuk et al., 2020]. On the other hand, [Chan and Grant, 2014] proves that Geometric Set Cover with unweighted axis-parallel rectangles is APX-hard; they also show similar hardness for Geometric Set Cover with many other standard geometric objects.

Parametrization We consider Geometric Set Cover parameterized by the size of solution. Geometric Set Cover with unit squares was first proven to be W[1]-hard in [Marx, 2005] (Theorem 5), later follow-up [Marx and Pilipczuk, 2015] shows that there is an algorithm running in time $\mathcal{O}(n^{\sqrt{k}})$ that solves Geometric Set Cover with unit squares or disks and that there is no algorithm running in time $f(k) \cdot n^{o(\sqrt{k})}$ for any computable f , so this is a tight bound for this problem.

We also consider parametrization of weighted problems. There does not seem to be a consensus of what parametrization in the weighted setting is exactly; there was an attempt to introduce a quite complicated general framework of weighted parameterized setting in [Shachnai and Zehavi, 2017]. Kernels for several well-known weighted problems such as Subset Sum or Knapsack are presented in [Etscheid et al., 2017]. Another work [Kim et al., 2021] considers weighted parametrization of Weighted Directed Feedback Set and Weighted *st*-Cut.

δ -extension In this paper, we focus on Geometric Set Cover with segments with δ -extension. δ -extension is a problem relaxation method based on the δ -shrinking model which was introduced in [Adamaszek et al., 2015] and later used in [Wiese, 2018] and [Pilipczuk et al., 2016].

Definition 1.2. For any $\delta > 0$ and a centre-symmetric strongly convex object L with centre of symmetry $S = (x_s, y_s)$, the δ -extension of L is the object $L^{+\delta} = \{(1 + \delta) \cdot (x - x_s, y - y_s) + (x_s, y_s) : (x, y) \in L\}$. That is, $L^{+\delta}$ is the image of L under homothety centred at S with scale $(1 + \delta)$.

Similar model is used to prove that Geometric Set Cover with fat polygons relaxed with δ -extension admits EPTAS [Har-Peled and Lee, 2009].

Our contribution

In this paper we make the following contributions.

We show that approximation of unweighted Geometric Set Cover with axis-parallel segments (even if we relax the problem with $\frac{1}{2}$ -extension) is APX-hard (Theorem 1.1).

Theorem 1.1. (*axis-parallel segment set cover with $\frac{1}{2}$ -extension is APX-hard*). *Unweighted geometric set cover with axis-parallel segments in the 2D plane (even with $\frac{1}{2}$ -extension) is APX-hard. That is, assuming $P \neq NP$, there does not exist a PTAS for this problem.*

This expands the previous result of Geometric Set Cover with unweighted axis-parallel rectangles being APX-hard in [Chan and Grant, 2014]. This also proves that the assumption in [Har-Peled and Lee, 2009] for EPTAS about polygons being fat is necessary, because cover with arbitrary polygons with δ -extension is APX-hard.

We also provide two FPT algorithms for parameterized Geometric Set Cover with unweighted segments (Theorem 1.2) and weighted segments relaxed with δ -extension (Theorem 1.3).

Theorem 1.2. (*FPT for segment cover*). *There exists an algorithm that given a family \mathcal{P} of segments (in any direction), a set of points \mathcal{C} and a parameter k , runs in time $k^{\mathcal{O}(k)}(|\mathcal{C}| \cdot |\mathcal{P}|)^2$, and outputs a solution $\mathcal{R} \subseteq \mathcal{P}$ such that $|\mathcal{R}| \leq k$ and \mathcal{R} covers all points in \mathcal{C} , or determines that such a set \mathcal{R} does not exist.*

Theorem 1.3. [*FPT for weighted segment cover with δ -extension*] *There exists an algorithm that given a family \mathcal{P} of n weighted segments (in any direction), a set of m points \mathcal{C} , and parameters k and $\delta > 0$, such that it runs in time $f(k, \delta) \cdot (nm)^c$ for some computable function f and a constant c and outputs a set \mathcal{R} such that:*

- $\mathcal{R} \subseteq \mathcal{P}$,
- $|\mathcal{R}| \leq k$,
- $\mathcal{R}^{+\delta}$ covers all points in \mathcal{C} ,
- the weight of \mathcal{R} is not greater than the weight of an optimum solution of size at most k for this problem without δ -extension

or determines that there is no set \mathcal{R} with $|\mathcal{R}| \leq k$ such that \mathcal{R} covers all points in \mathcal{C} .

131 On the other hand Geometric Set Cover with weighted axis-parallel segments is $W[1]$ -hard
132 (Theorem 1.4) and assuming ETH there does not exist algorithm for this problem that runs
133 in time $f(k)(|\mathcal{C}| + |\mathcal{P}|)^{o(\sqrt{k})}$. See Figure 1.1 for a summary of parameterized results for the
134 weighted setting.

135 **Theorem 1.4.** *Consider the problem of covering a set \mathcal{C} of points by selecting at most k*
136 *segments from a set of segments \mathcal{P} with non-negative weights $w : \mathcal{P} \rightarrow \mathbb{R}^+$ so that the weight*
137 *of the cover is minimal. Then this problem is $W[1]$ -hard when parameterized by k and assuming*
138 *ETH, there is no algorithm for this problem with running time $f(k) \cdot (|\mathcal{C}| + |\mathcal{P}|)^{o(\sqrt{k})}$ for any*
139 *computable function f . Moreover, this holds even if all segments in \mathcal{P} are axis-parallel or*
140 *right-diagonal.*

141 Please see Section 2.1 for exact definitions of axis-parallel and right-diagonal segments.

142 TODO: Write something about permissive as a side thingy

143 This result is not tight. There exists a simple algorithm running in time $\mathcal{O}(f(k)(|\mathcal{C}| + |\mathcal{P}|)^k)$,
144 so the question whether there exists an algorithm for this problem running in time $f(k) \cdot (|\mathcal{C}| + |\mathcal{P}|)^{o(k)}$
145 is still open.

	exact	δ -extension
axis-parallel	?	FPT*
3 directions	$W[1]$ -hard	FPT*
any direction	$W[1]$ -hard*	FPT

Figure 1.1: Our results for Geometric Set Cover problem with weighted segments parameterized by the size of solution. Results marked with * directly follow from more or less restricted settings.

146 Chapter 2

147 Definitions

148 In this chapter we present some basic definitions that will be used later.

149 2.1. Geometric set cover

150 Whenever speaking about geometric set cover, we consider it in the 2-dimensional plane.

151 In the geometric set cover problem we are given \mathcal{P} — a set of objects, which are
152 connected subsets of the plane and \mathcal{C} — a set of points in the plane. The task is to choose
153 $\mathcal{R} \subseteq \mathcal{P}$ such that every point in \mathcal{C} is inside some object from \mathcal{R} and $|\mathcal{R}|$ is minimized. We
154 will mostly consider the case where \mathcal{P} consists of segments in the plane.

155 In the parameterized setting for a given k , our task is to either find a solution \mathcal{R} such that
156 $|\mathcal{R}| \leq k$ or decide that there is no such solution.

157 In the weighted setting, there is some given weight function $f : \mathcal{P} \rightarrow \mathbb{R}^+$ and we would
158 like to find a solution \mathcal{R} that minimizes $\sum_{R \in \mathcal{R}} f(R)$.

159 **Definition 2.1.** Segment is **axis-parallel** if it lies on line that is either horizontal $x = c$ or
160 vertical $y = c$.

161 **Definition 2.2.** A line is **right-diagonal** if it is described by linear function $x + y = d$ for
162 some $d \in \mathbb{R}$. Segment is **right-diagonal** if its direction is a right-diagonal line.

163 2.2. Approximation

164 Let us recall some definitions related to optimization problems.

165 **Definition 2.3.** A **polynomial-time approximation scheme (PTAS)** for a minimization
166 problem Π is a family of algorithms \mathcal{A}_ϵ for every $\epsilon > 0$ such that \mathcal{A}_ϵ takes an instance I of Π
167 and in polynomial time finds a solution that is within a factor of $(1 + \epsilon)$ of being optimal.
168 This means that the reported solution has weight at most $(1 + \epsilon)\text{opt}(I)$, where $\text{opt}(I)$ is the
169 weight of an optimal solution to I .

170 **Definition 2.4.** A problem Π is **APX-hard** if assuming $P \neq NP$, there exists $\epsilon > 0$ such
171 that there is no polynomial-time $(1 + \epsilon)$ -approximation algorithm for Π .

172 2.3. δ -extension

173 Another idea presented here, which can be utilized only when considering the problems with
174 geometric objects, is δ -extension. We define it specifically for the geometric set cover problem.

Intuitively, we consider a problem with slightly larger objects, which makes the instance more permissive. However, we aim to find a solution that is not larger than the optimum solution to the original problem, so this is substantially easier than just solving the problem for the larger objects. It may even be the case that we are able to find a solution of size smaller than the optimum solution to the original problem.

Formal definition of δ -extended objects. is present in Definition 1.2.

The geometric set cover problem with δ -extension is a version of geometric set cover with the following modifications.

- We need to cover all the points in \mathcal{C} by selecting objects from $\{P^{+\delta} : P \in \mathcal{P}\}$ (which always include no fewer points than the objects before δ -extension).
- We look for a solution that is not larger than the optimum solution to the original problem. Note that it does not need to be an optimal solution in the modified problem.

Formally, we have the following.

Definition 2.5. The **geometric set cover problem with δ -extension** is the problem where for an input instance $I = (\mathcal{P}, \mathcal{C})$ of geometric set cover, the task is to output a solution $\mathcal{R} \subseteq \mathcal{P}$ such that the δ -extended set $\{R^{+\delta} : R \in \mathcal{R}\}$ covers \mathcal{C} and is not larger than the optimal solution to the problem without extension, i.e. $|\mathcal{R}| \leq |\text{opt}(I)|$.

At last, we formulate a definition of the polynomial-time approximation scheme (PTAS) for a problem with δ -extension.

Definition 2.6. A **PTAS for geometric set cover with δ -extension** is a family of algorithms $\{\mathcal{A}_{\delta, \epsilon}\}_{\delta, \epsilon > 0}$ that each takes as an input instance $I = (\mathcal{P}, \mathcal{C})$ of geometric set cover where objects are centre-symmetric and strongly convex, and in polynomial-time outputs a solution $\mathcal{R} \subseteq \mathcal{P}$ such that the δ -extended set $\{R^{+\delta} : R \in \mathcal{R}\}$ covers \mathcal{C} and is within a $(1 + \epsilon)$ factor of the optimal solution to this problem without extension, i.e. $(1 + \epsilon)|\mathcal{R}| \leq |\text{opt}(I)|$.

2.4. Weighted setting

In this thesis we also consider a weighted parameterized setting, which is a combination of the weighted and parameterized setting described in 2.1. We already argued in the introduction that there is no consensus of how it is defined, but when we discuss the weighted parametrized setting we will consider the following definition. There is a given weight function $f : \mathcal{P} \rightarrow \mathbb{R}^+$ and we would like to find a solution \mathcal{R} , such that $|\mathcal{R}| \leq k$ that minimizes $\sum_{R \in \mathcal{R}} f(R)$ among such sets \mathcal{R} .

We also consider weighted parameterized setting with δ -extension, which we formally define below.

TODO: Restate below for FPT

Definition 2.7. The **weighted geometric set cover problem with δ -extension** is the problem where for an input instance $I = (\mathcal{P}, \mathcal{C}, f)$ of weighted geometric set cover, the task is to output a solution $\mathcal{R} \subseteq \mathcal{P}$ such that the δ -extended set $\{R^{+\delta} : R \in \mathcal{R}\}$ covers \mathcal{C} and is not larger than the optimal solution to the problem without extension, i.e. $\sum_{R \in \mathcal{R}} f(R) \leq |\text{opt}(I)|$.

Chapter 3

APX-hardness of geometric set cover problem

In this section we analyze whether there exists a PTAS for geometric set cover for rectangles. We show that we can restrict this problem to a very simple setting: segments parallel to axes and allow $(1/2)$ -extension, and the problem is still APX-hard. Note that segments are just degenerated rectangles with one side being very narrow.

Our results can be summarized in the following theorem and this section aims to prove it.

Theorem 1.1. *(axis-parallel segment set cover with $\frac{1}{2}$ -extension is APX-hard). Unweighted geometric set cover with axis-parallel segments in the 2D plane (even with $\frac{1}{2}$ -extension) is APX-hard. That is, assuming $P \neq NP$, there does not exist a PTAS for this problem.*

Theorem 1.1 implies the following.

Corollary 3.1. *(rectangle set cover is APX-hard). Unweighted geometric set cover with axis-parallel rectangles (even with $1/2$ -extension) is APX-hard.*

We prove Theorem 1.1 by taking a problem that is APX-hard and showing a reduction. For this problem we choose MAX-(3,3)-SAT which we define below.

3.1. MAX-(3,3)-SAT and statement of reduction

Definition 3.1. MAX-3SAT is the following maximization problem. We are given a 3-CNF formula, and need to find an assignment of variables that satisfies the most clauses.

Definition 3.2. MAX-(3,3)-SAT is a variant of MAX-3SAT with an additional restriction that every variable appears in exactly 3 clauses and every clause contains exactly 3 literals of 3 different variables. Note that thus, the number of clauses is equal to the number of variables.

In our proof of Theorem 1.1 we use hardness of approximation of MAX-(3,3)-SAT proved in [Håstad, 2001] and described in Theorem 3.1 below.

Definition 3.3 (α -satisfiable MAX-3SAT formula). MAX-3SAT formula with m clauses is at most α -satisfiable, if every assignment of variables satisfies no more than αm clauses.

Theorem 3.1. [Håstad, 2001] *For any $\epsilon > 0$, it is NP-hard to distinguish satisfiable (3,3)-SAT formulas from at most $(7/8 + \epsilon)$ -satisfiable (3,3)-SAT formulas.*

Given an instance I of MAX-(3,3)-SAT, we construct an instance J of axis-parallel segment set cover problem such that for a sufficiently small $\epsilon > 0$, a polynomial time $(1 + \epsilon)$ -approximation algorithm for J would be able to distinguish whether an instance I of MAX-(3,3)-SAT is fully satisfiable or is at most $(7/8 + \epsilon)$ -satisfiable. However, according to Theorem 3.1 the latter problem is NP-hard. This would imply $P = NP$, contradicting the assumption.

The following lemma encapsulates the properties of the reduction described in this section, and it allows us to prove Theorem 1.1.

Lemma 3.1. *Given an instance S of MAX-(3,3)-SAT with n variables and optimum value $opt(S)$, we can construct an instance I of geometric set cover with axis-parallel segments in 2D such that:*

(1) *For every solution X of instance I , there exists a solution to S that satisfies at least $15n - |X|$ clauses.*

(2) *For every solution to instance S that satisfies w clauses, there exists a solution to I of size $15n - w$.*

(3) *Every solution with $1/2$ -extension of I is also a solution to the original instance I .*

Therefore, the optimum size of a solution to I is $opt(I) = 15n - opt(S)$.

We prove Lemma 3.1 in subsequent sections, but meanwhile let us prove Theorem 1.1 using Lemma 3.1 and Theorem 3.1.

Proof of Theorem 1.1. Consider any $0 < \epsilon < 1/(15 \cdot 8)$.

Let us assume that there exists a polynomial-time $(1 + \epsilon)$ -approximation algorithm for unweighted geometric set cover with axis-parallel segments in 2D with $(1/2)$ -extension. We construct an algorithm that solves the problem stated in Theorem 3.1, thereby proving that $P = NP$.

Take an instance S of MAX-(3,3)-SAT to be distinguished and construct an instance of geometric set cover I using Lemma 3.1. We now use the $(1 + \epsilon)$ -approximation algorithm for geometric set cover on I . Denote the size of the solution returned by this algorithm as $approx(I)$. We prove that if in S one can satisfy at most $(\frac{7}{8} + \epsilon)n$ clauses, then $approx(I) \geq 15n - (\frac{7}{8} + \epsilon)n$ and if S is satisfiable, then $approx(I) < 15n - (\frac{7}{8} + \epsilon)n$.

Assume S satisfiable. From the definition of S being satisfiable, we have:

$$opt(S) = n.$$

From Lemma 3.1 we have:

$$opt(I) = 14n.$$

Therefore,

$$\begin{aligned} approx(I) &\leq (1 + \epsilon)opt(I) = 14n(1 + \epsilon) = 14n + 14\epsilon \cdot n = \\ &= 14n + (15\epsilon - \epsilon)n < 14n + \left(\frac{1}{8} - \epsilon\right)n = 15n - \left(\frac{7}{8} + \epsilon\right)n. \end{aligned}$$

Assume S is at most $(\frac{7}{8} + \epsilon)$ satisfiable. From the definition of S being at most $(\frac{7}{8} + \epsilon)$ satisfiable, we have:

$$opt(S) \leq \left(\frac{7}{8} + \epsilon\right)n$$

From Lemma 3.1 we have:

$$opt(I) \geq 15n - \left(\frac{7}{8} + \epsilon\right)n$$

271 Since a solution to I with $\frac{1}{2}$ -extension is also a solution without any extension, by Lemma
272 3.1 (3), we have:

$$approx(I) \geq opt(I) = 15n - \left(\frac{7}{8} + \epsilon\right)n$$

273 Therefore, by using the assumed $(1 + \epsilon)$ -approximation algorithm, it is possible to distin-
274 guish the case when S is satisfiable: from the case when it is at most $(\frac{7}{8} + \epsilon)n$ satisfiable,
275 it suffices to compare $approx(I)$ with $15n - (\frac{7}{8} + \epsilon)n$. Hence, the assumed approximation
276 algorithm cannot exist, unless $P = NP$. \square

277 3.2. Reduction

278 We proceed to the proof of Lemma 3.1. That is, we show a reduction from the MAX-(3,3)-
279 SAT problem to geometric set cover with segments parallel to axis. Moreover, the obtained
280 instance of geometric set cover will be robust to 1/2-extension (have the same optimal solution
281 after 1/2-extension).

282 The construction will be composed of 2 types of gadgets: **VARIABLE-gadgets** and
283 **CLAUSE-gadgets**. **CLAUSE-gadgets** will be constructed using two **OR-gadgets** connected
284 together.

285 3.2.1. VARIABLE-gadget

286 **VARIABLE-gadget** is responsible for choosing the value of a variable in a CNF formula. It
287 allows two minimum solutions of size 3 each. These two choices correspond to the two Boolean
288 values of the variable corresponding to this gadget.

289 **Points.** Define points a, b, c, d, e, f, g, h as follows, where $L = 22n$:

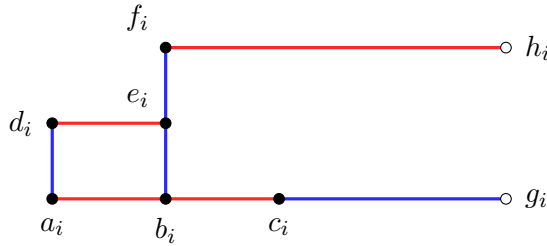


Figure 3.1: **VARIABLE-gadget**. We denote the set of points marked with black circles as pointsVariable_i , and they need to be covered (are part of the set \mathcal{C}). Note that some of the points are not marked as black dots and exists only to name segments for further reference. We denote the set of red segments as $\text{chooseVariable}_i^{\text{false}}$ and the set of blue segments as $\text{chooseVariable}_i^{\text{true}}$.

290

$$\begin{array}{llll} a = (-3L, 0) & b = (-2L, 0) & c = (-L, 0) & d = (-3L, 1) \\ e = (-2L, 1) & f = (-2L, 2) & g = (L, 0) & h = (L, 2) \end{array}$$

Let us define:

$$\text{pointsVariable} = \{a, b, c, d, e, f\}$$

and, for any $1 \leq i \leq n$,

$$\text{pointsVariable}_i = \text{pointsVariable} + (0, 4i).$$

291 We denote $a_i := a + (0, 4i)$ etc.

292 **Segments.** Let us define:

$$\text{chooseVariable}_i^{\text{true}} := \{(a_i, d_i), (b_i, f_i), (c_i, g_i)\},$$

$$\text{chooseVariable}_i^{\text{false}} := \{(a_i, c_i), (d_i, e_i), (f_i, h_i)\},$$

$$\text{segmentsVariable}_i := \text{chooseVariable}_i^{\text{true}} \cup \text{chooseVariable}_i^{\text{false}}.$$

293 We also name two of these segment for future reference: $\text{xTrueSegment}_i := (c_i, g_i)$,
294 $\text{xFalseSegment}_i := (f_i, h_i)$.

295 **Lemma 3.2.** *For any $1 \leq i \leq n$, points in pointsVariable_i can be covered using 3 segments*
296 *from $\text{segmentsVariable}_i$.*

297 *Proof.* We can use either set $\text{chooseVariable}_i^{\text{true}}$ or $\text{chooseVariable}_i^{\text{false}}$. □

298 **Lemma 3.3.** *For any $1 \leq i \leq n$, points in pointsVariable_i can not be covered with fewer than*
299 *3 segments from $\text{segmentsVariable}_i$.*

300 *Proof.* No segment of $\text{segmentsVariable}_i$ covers more than one point from $\{d_i, f_i, c_i\}$, therefore
301 pointsVariable_i can not be covered with fewer than 3 segments. □

302 **Lemma 3.4.** *For every set $A \subseteq \text{segmentsVariable}_i$ such that A covers pointsVariable_i and*
303 *$\text{xTrueSegment}_i, \text{xFalseSegment}_i \in A$, it holds that $|A| \geq 4$.*

304 *Proof.* No segment from $\text{segmentsVariable}_i$ covers more than one point from $\{a_i, e_i\}$, therefore
305 $\text{pointsVariable}_i - \{c_i, f_i, g_i, h_i\}$ can not be covered with fewer than 2 segments. □

306 3.2.2. OR-gadget

307 OR-gadget connects input and output segments (see Figure 3.2) in a way that is supposed to
308 simulate a binary *or* function.

309 Input segments are the only segments that cover points outside of the gadget, as their left
310 ends lie outside of it. Point $v_{i,j}$ is the only one that can be covered by segments that do not
311 belong to the gadget.

312 The OR-gadget has the property that every set of segments that covers all the points in
313 the gadget uses at least 3 segments from it.. Moreover, the output segment belongs to the
314 solution of size 3 only if at least one of the input segments belong to the solution. Therefore,
315 optimum solutions restricted to the OR-gadget behave like a binary *or* function for the input
316 segments.

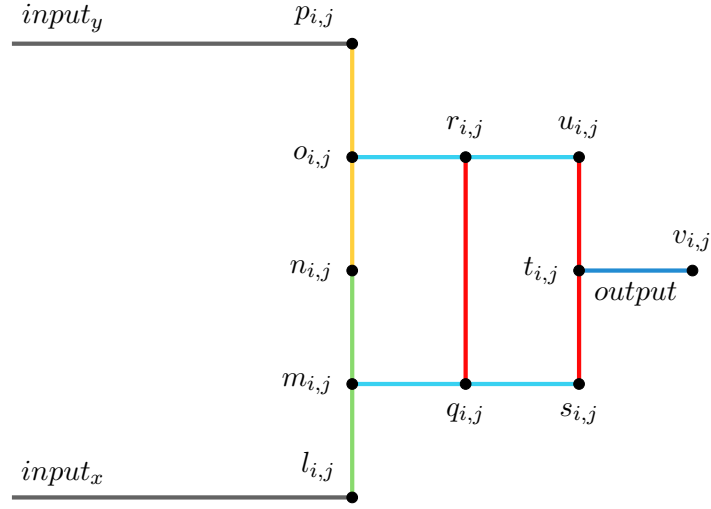


Figure 3.2: **OR-gadget**. Segments from $\text{chooseOr}_{i,j}^{false}$ are **red**, segments from $\text{chooseOr}_{i,j}^{true}$ are blue (both **light blue** and **dark blue**), segments from $\text{orMoveVariable}_{i,j}$ are **green** and **yellow**. **Dark blue** segment is the *output* segment. Grey segments input_x and input_y are input segments that are not part of $\text{segmentsOr}_{i,j}$.

317 **Points.**

$$\begin{aligned}
 l_0 &:= (0, 0) & m_0 &:= (0, 1) & n_0 &:= (0, 2) & o_0 &:= (0, 3) \\
 p_0 &:= (0, 4) & q_0 &:= (1, 1) & r_0 &:= (1, 3) & s_0 &:= (2, 1) \\
 t_0 &:= (2, 2) & u_0 &:= (2, 3) & v_0 &:= (3, 2)
 \end{aligned}$$

$$\text{vec}_{i,j} := (20i + 3 + 3j, 4(n + 1) + 2j)$$

319 For integers i, j , define $\{l_{i,j}, m_{i,j} \dots v_{i,j}\}$ as $\{l_0, m_0 \dots v_0\}$ shifted by $\text{vec}_{i,j}$, i.e. $l_{i,j} =$
 320 $l_0 + \text{vec}_{i,j}$ etc.

321 Note that $v_{i,0} = l_{i,1}$ (see Figure 3.3)

$$\text{pointsOr}_{i,j} := \{l_{i,j}, m_{i,j}, n_{i,j}, o_{i,j}, p_{i,j}, q_{i,j}, r_{i,j}, s_{i,j}, t_{i,j}, u_{i,j}\}$$

322 Note that $\text{pointsOr}_{i,j}$ does not include the point $v_{i,j}$

323 **Segments.** We define set of segments in several parts:

$$\begin{aligned}
 \text{chooseOr}_{i,j}^{false} &:= \{(q_{i,j}, r_{i,j}), (s_{i,j}, u_{i,j})\}, \\
 \text{chooseOr}_{i,j}^{true} &:= \{(m_{i,j}, s_{i,j}), (o_{i,j}, u_{i,j}), (t_{i,j}, v_{i,j})\},
 \end{aligned}$$

$$\text{orMoveVariable}_{i,j} := \{(l_{i,j}, n_{i,j}), (n_{i,j}, p_{i,j})\}.$$

324 Finally all segments in OR-gadget are defined as:

$$\text{segmentsOr}_{i,j} := \text{chooseOr}_{i,j}^{false} \cup \text{chooseOr}_{i,j}^{true} \cup \text{orMoveVariable}_{i,j}$$

325 **Lemma 3.5.** For any $1 \leq i \leq n, j \in \{0, 1\}$ and $x \in \{l_{i,j}, p_{i,j}\}$, points in $\text{pointsOr}_{i,j} - \{x\} \cup$
 326 $\{v_{i,j}\}$ can be covered with 4 segments from $\text{segmentsOr}_{i,j}$.

327 *Proof.* We can do that using one segment from $\text{orMoveVariable}_{i,j}$, the one that does not cover
 328 x , and all segments from $\text{chooseOr}_{i,j}^{\text{true}}$. \square

329 **Lemma 3.6.** *For any $1 \leq i \leq n, j \in \{0,1\}$, points in $\text{pointsOr}_{i,j}$ can be covered with 4*
 330 *segments from $\text{segmentsOr}_{i,j}$.*

331 *Proof.* We can do that using segments from $\text{orMoveVariable}_{i,j} \cup \text{chooseOr}_{i,j}^{\text{false}}$. \square

332 3.2.3. CLAUSE-gadget

333 A CLAUSE-gadget is responsible for determining whether variable values assigned in variable
 334 gadgets satisfy the corresponding clause in the input formula ϕ . It has a minimum solution
 335 to weight w if and only if the clause is satisfied, i.e. at least one of the respective variables is
 336 assigned the correct value. Otherwise, its minimum solution has weight $w + 1$. In this way,
 337 by analyzing the cost of the minimum solution to the entire constructed instance, we will be
 338 able to tell how many clauses it was possible to satisfy in the optimum solution to ϕ .

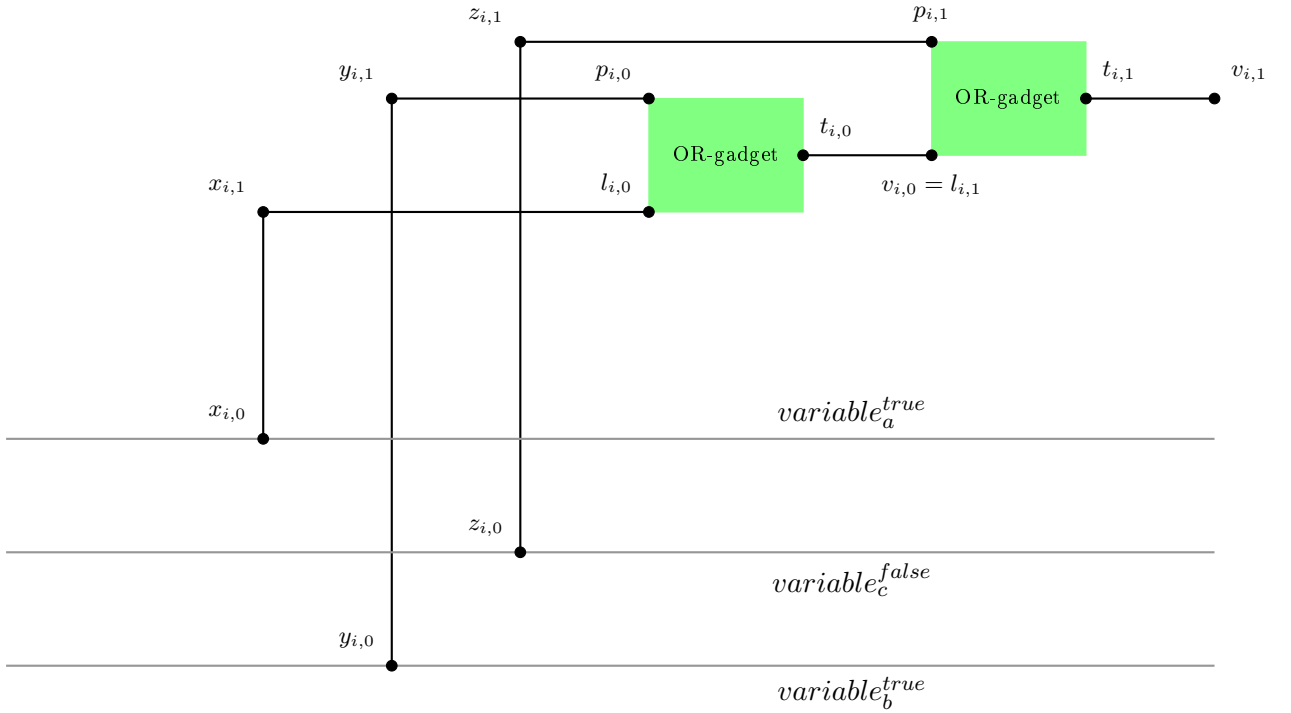


Figure 3.3: **CLAUSE-gadget for a clause $a \vee b \vee \neg c$.** Every green rectangle is an OR-gadget. y -coordinates of $x_{i,0}, y_{i,0}$ and $z_{i,0}$ depend on the variables in the i -th clause. Grey segments corresponds to the values of variables satisfying the i -th clause.

339 **Points.** First, we define auxiliary functions for literals. For a literal w , let $\text{idx}(w)$ be the
 340 index of the variable in w , and $\text{neg}(w)$ be the Boolean value whether the variable is negated
 341 in w or not.

342 Let us assume that clause $C_i = a \vee b \vee c$ for any literals a, b, c . Then, we define points in
 343 the gadget as:

$$\begin{aligned}
x_{i,0} &:= (20i, 4 \cdot \text{id}x(a) + 2 \cdot \text{neg}(c)), & x_{i,1} &:= (20i, 4(n+1)), \\
y_{i,0} &:= (20i+1, 4 \cdot \text{id}x(b) + 2 \cdot \text{neg}(b)), & y_{i,1} &:= (20i+1, 4(n+1)+4), \\
z_{i,0} &:= (20i+2, 4 \cdot \text{id}x(c) + 2 \cdot \text{neg}(c)), & z_{i,1} &:= (20i+2, 4(n+1)+6).
\end{aligned}$$

We are now ready to define set of points:

$$\text{moveVariable}_i := \{x_{i,j} : j \in \{0,1\}\} \cup \{y_{i,j} : j \in \{0,1\}\} \cup \{z_{i,j} : j \in \{0,1\}\},$$

$$\text{pointsClause}_i := \text{moveVariable}_i \cup \text{pointsOr}_{i,0} \cup \text{pointsOr}_{i,1} \cup \{v_{i,1}\}.$$

Note that these two points are equal: $v_{i,0} = l_{i,1}$. This translates to the fact, that output of the one OR-gadget is an input to the other OR-gadget to create *or* of 3 segments.

Segments. We also define segments for the clause gadget as below:

$$\begin{aligned}
\text{segmentsClause}_i &:= \{(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1}), (x_{i,1}, l_{i,0}), (y_{i,1}, p_{i,0}), (z_{i,1}, p_{i,1}), \} \cup \\
&\cup \text{segmentsOr}_{i,0} \cup \text{segmentsOr}_{i,1}.
\end{aligned}$$

The CLAUSE-gadgets consist of two OR-gadgets. Ideally, we would place the i -th CLAUSE-gadget close to the $\text{xTrueSegment}_{j_1}$ or $\text{xFalseSegment}_{j_1}$ segments corresponding to the literals that occur in the i -th clause. It would be inconvenient to position them there, because between these segments there may be additional $\text{xTrueSegment}_{j_2}$ or $\text{xFalseSegment}_{j_2}$ segments corresponding to the other literals.

Instead, we use simple auxiliary gadgets to *transfer* whether the segment is in a solution, i.e. segments $(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1})$ in this gadget. Each gadget consists of two segments $(x_{i,0}, x_{i,1}), (x_{i,1}, a)$. These are the only segments that can cover $x_{i,1}$. We place $x_{i,0}$ on a segment that we want to transfer (i.e. segment responsible for choosing the variable value satisfying the corresponding literal). If in some solution $x_{i,0}$ is already covered by this segment, then we can cover $x_{i,1}$ by $(x_{i,1}, a)$, thus also covering a . If $x_{i,0}$ is not covered by this segment, then the only way to cover $x_{i,0}$ is to use segment $(x_{i,0}, x_{i,1})$. Intuitively, in any optimal solution the two segments *transfer* the state of whether $x_{i,0}$ is covered onto whether a is covered. Therefore, the number of segments in the optimal solution is increased by one, and we get a point a that was effectively placed on some segment s , but it can be placed anywhere in the plane instead, consequently simplifying the construction.

Lemma 3.7. *For any $1 \leq i \leq n$ and $a \in \{x_{i,0}, y_{i,0}, z_{i,0}\}$, there is a set $\text{solClause}_i^{\text{true},a} \subseteq \text{segmentsClause}_i$ with $|\text{solClause}_i^{\text{true},a}| = 11$ that covers all points in $\text{pointsClause}_i - \{a\}$.*

Proof. For $a = x_{i,0}$ (analogous proof for $y_{i,0}$): First we use Lemma 3.5 twice with excluded $x = l_{i,0}$ and $x = l_{i,1} = v_{i,0}$, resulting with 8 segments in $\text{chooseOr}_{i,0}^{\text{true}} \cup \text{chooseOr}_{i,1}^{\text{true}}$ which cover all required points apart from $x_{i,1}, y_{i,0}, y_{i,1}, z_{i,0}, z_{i,1}, l_{i,0}$. We cover those using additional 3 segments: $\{(x_{i,1}, l_{i,0}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1})\}$

For $a = z_{i,0}$: Using Lemma 3.6 and Lemma 3.5 with $x = p_{i,1}$, we obtain 8 segments in $\text{chooseOr}_{i,0}^{\text{false}} \cup \text{chooseOr}_{i,1}^{\text{true}}$ which cover all required points apart from $x_{i,0}, x_{i,1}, y_{i,0}, y_{i,1}, z_{i,1}, p_{i,1}$. We cover those using additional 3 segments: $\{(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,1}, p_{i,1})\}$. \square

Lemma 3.8. *For any $1 \leq i \leq n$ there is a set $\text{solClause}_i^{\text{false}} \subseteq \text{segmentsClause}_i$ with $|\text{solClause}_i^{\text{false}}| = 12$ that covers all points in pointsClause_i .*

376 *Proof.* Using Lemma 3.6 twice we can cover $\text{pointsOr}_{i,0}$ and $\text{pointsOr}_{i,1}$ with 8 segments. To
 377 cover the remaining points we additionally use: $\{(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1}), (t_{i,1}, v_{i,1})\}$
 378 \square

379 **Lemma 3.9.** *For any $1 \leq i \leq n$:*

- 380 (1) *points in pointsClause_i can not be covered using any subset of segments from segmentsClause_i*
 381 *of size smaller than 12;*
- 382 (2) *points in $\text{pointsClause}_i - \{x_{i,0}, y_{i,0}, z_{i,0}\}$ can not be covered using any subset of segments*
 383 *from segmentsClause_i of size smaller than 11.*

Proof of (1). No segment in segmentsClause_i covers more than 1 point from

$$\{x_{i,0}, y_{i,0}, z_{i,0}, l_{i,0}, p_{i,0}, q_{i,0}, u_{i,0}, v_{i,0} = l_{i,1}, p_{i,1}, q_{i,1}, u_{i,1}, v_{i,1}\}.$$

384 Therefore we need to use at least 12 segments. \square

385 *Proof of (2).* We can define disjoint sets X, Y, Z such that $X \cup Y \cup Z \subseteq \text{pointsClause}_i -$
 386 $\{x_{i,0}, y_{i,0}, z_{i,0}\}$ such that there are no segments in segmentsClause_i covering points from dif-
 387 ferent sets. And we prove a lower bound for each of these sets. First, let:

$$X := \{x_{i,1}, y_{i,1}, z_{i,1}\}.$$

388 No two points in X can be covered with one segment of segmentsClause_i , so it must be
 389 covered with 3 different segments. Next we define other sets:

$$Y := \text{pointsOr}_{i,0} - \{l_{i,0}, p_{i,0}\},$$

$$Z := \text{pointsOr}_{i,1} - \{l_{i,1}, p_{i,1}\}.$$

390 For both Y and Z we can check all of the subsets of 3 segments of segmentsClause_i to
 391 conclude that none of them cover the considered, so both Y and Z have to be covered with
 392 disjoint sets of 4 segments each.

393 Therefore, $\text{pointsClause}_i - \{x_{i,0}, y_{i,0}, z_{i,0}\}$ must be covered with at least $3 + 4 + 4 = 11$
 394 segments from segmentsClause_i . \square

395 3.2.4. Summary

396 Add some smart lemmas that sets will be exclusive to each other.

397 **Lemma 3.10. Robustness to 1/2-extension.** *For every segment $s \in \mathcal{P}$, s and $s^{+\frac{1}{2}}$ cover*
 398 *the same points from \mathcal{C} .*

399 *Proof.* We can just check every segment. Most of the segments s are collinear only with points
 400 that lie on s , so trivially $s^{+\frac{1}{2}}$ cannot cover more points than s does.

401 Within VARIABLE-gadget for any $1 \leq i \leq n$ after $\frac{1}{2}$ -extension: (c_i, g_i) does not cover b_i .

402 Within OR-gadget some of the segments are collinear and share one point; specifically, for
 403 any $1 \leq i \leq n$ and $j \in \{0, 1\}$, after $\frac{1}{2}$ -extension:

- 404 • $(l_{i,j}, n_{i,j})$ does not cover $o_{i,j}$,
- 405 • $(n_{i,j}, p_{i,j})$ does not cover $m_{i,j}$,
- 406 • $(t_{i,j}, v_{i,j})$ does not cover $n_{i,j}$.

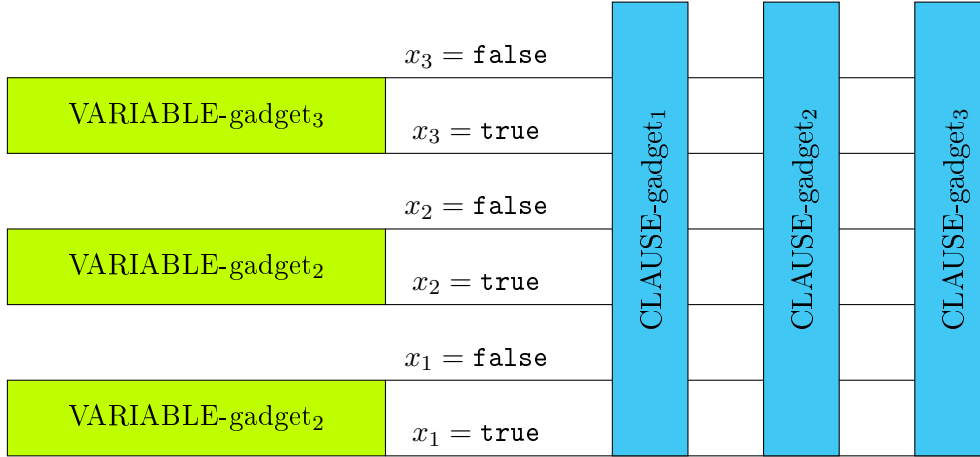


Figure 3.4: **Schema of the whole construction.**

General layout of VARIABLE-gadgets and CLAUSE-gadgets and how they interact with each other.

407 Within CLAUSE-gadget, for any $1 \leq i \leq n$ after $\frac{1}{2}$ -extension:

- 408 • $(o_{i,0}, u_{i,0})$ does not cover $m_{i,1}$,
- 409 • $(m_{i,1}, s_{i,1})$ does not cover $u_{i,0}$,
- 410 • $(y_{i,1}, p_{i,0})$ does not cover $n_{i,1}$.

411 For two consecutive VARIABLE-gadgets, for any $1 \leq i < n$ after $\frac{1}{2}$ -extension: (b_i, f_i) does
 412 not cover b_{i+1} (nor f_{i-1} for $i > 1$). Similarly (a_i, d_i) does not cover a_{i+1} (nor d_{i-1} for $i > 1$),
 413 because this segment is shorter than the previous one and a_i and b_i share y-coordinate.

414 For two consecutive CLAUSE-gadgets, segments from one do not cover anything from the
 415 other, as the gadgets have width 9 and every leftmost x-coordinate is divisible by 20. Hence
 416 two different gadgets do not interact with each other after $\frac{1}{2}$ -extension.

417 Next we need to check whether VARIABLE-gadget's segments do not cover any points
 418 $x_{i,0}, y_{i,0}$ or $z_{i,0}$ from CLAUSE-gadget. For any $1 \leq i \leq n$ and $1 \leq j \leq n$, all points $x_{j,0}, y_{j,0}$
 419 and $z_{j,0}$ have x-coordinate strictly positive. Segment (a_i, c_i) have length $2L$ and c_i has x-
 420 coordinate equal to $-L$, so after $\frac{1}{2}$ -extension this segment does not cover any points with a
 421 positive x-coordinate.

422 □

423 3.2.5. Summary of construction

Finally we define set of points and segments for the constructed instance:

$$\mathcal{C} := \bigcup_{1 \leq i \leq n} \text{pointsVariable}_i \cup \text{pointsClause}_i,$$

$$\mathcal{P} := \bigcup_{1 \leq i \leq n} \text{segmentsVariable}_i \cup \text{segmentsClause}_i.$$

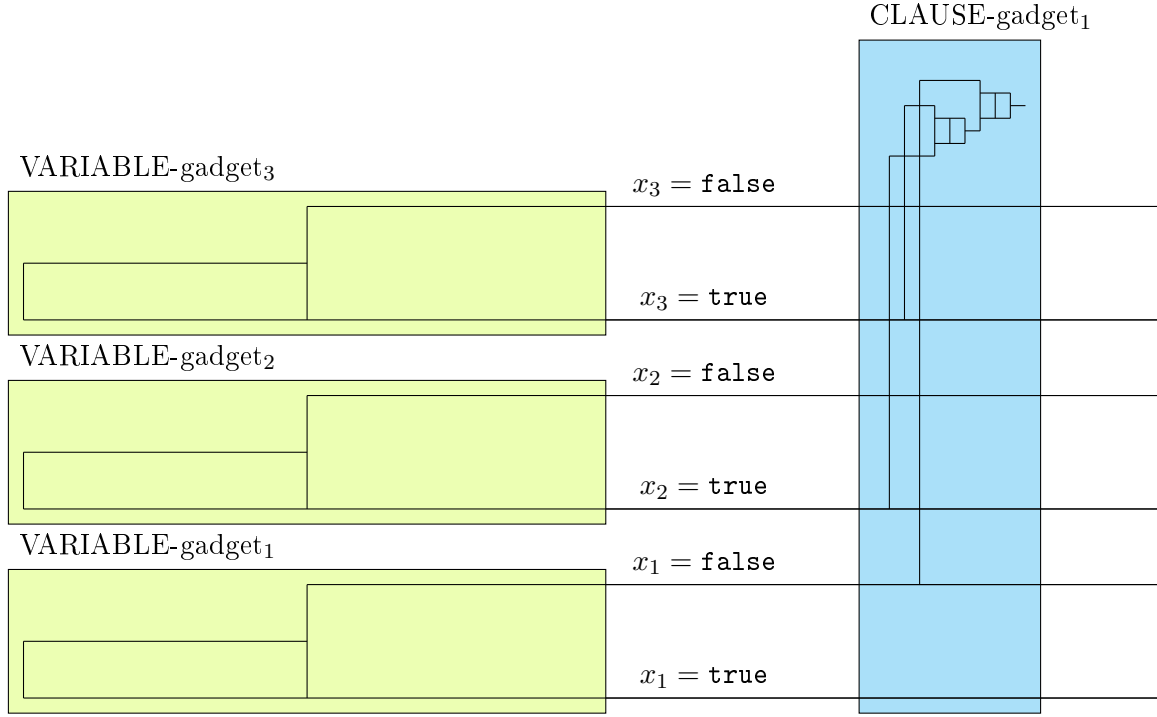


Figure 3.5: **Schema of the whole construction.**

General layout of VARIABLE-gadgets and CLAUSE-gadgets and how they interact with each other.

3.3. Construction lemmas and proof of Lemma 3.1

In order to prove Lemma 3.1 we introduce several auxiliary lemmas proving properties of the construction described in the previous section.

Consider an instance S of MAX-(3,3)-SAT of size n with optimum solution satisfying k clauses. Let us construct an instance $(\mathcal{C}, \mathcal{P})$ of geometric set cover as described in Section 3.2 for the instance S of MAX-(3,3)-SAT.

Lemma 3.11. *Instance $(\mathcal{C}, \mathcal{P})$ of geometric set cover admits a solution of size $15n - k$.*

Proof. Let the clauses in S be $c_1, c_2 \dots c_n$ and the variables be $x_1, x_2 \dots x_n$. Let the variable assignment in the optimum solution to S be $\phi : \{x_1, x_2 \dots x_n\} \rightarrow \{\mathbf{true}, \mathbf{false}\}$.

We cover every VARIABLE-gadget with solution described in Lemma 3.2, where in the i -th gadget we choose the set of segments corresponding to the value of $\phi(x_i)$.

For every clause that is satisfied, say c_i , let us name the variable that is **true** in it as x_i and point corresponding to x_i in $\mathbf{pointsClause}_i$ as a . Points in $\mathbf{pointsClause}_i$ are covered with set $\mathbf{solClause}_i^{\mathbf{true}, a}$ described in Lemma 3.7. For every clause that is not satisfied, say c_j , points in $\mathbf{pointsClause}_j$ are covered with set $\mathbf{solClause}_j^{\mathbf{false}}$ described in Lemma 3.8.

Formally we define sets responsible for choosing variable assignment and satisfying clauses, R_i and C_i respectively, as following:

$$\begin{aligned}
R_i &:= \begin{cases} \text{chooseVariable}_i^{\text{true}} & \text{if } \phi(x_i) = \text{true} \\ \text{chooseVariable}_i^{\text{false}} & \text{if } \phi(x_i) = \text{false} \end{cases} \\
C_i &:= \begin{cases} \text{solClause}_i^{\text{true},a} & \text{if } c_i \text{ satisfied by literal corresponding to point } a \\ \text{solClause}_i^{\text{false}} & \text{if } c_i \text{ not satisfied} \end{cases} \\
\mathcal{R} &:= \bigcup_{i=1}^n \{R_i \cup C_i : 1 \leq i \leq n\}.
\end{aligned}$$

441 This set covers all the points from \mathcal{C} , because the sets R_i , C_i individually cover their
442 corresponding gadgets, as proved in the respective lemmas.

443 All of these sets are disjoint, so the size of the obtained solution is:

$$|\mathcal{R}| = \sum_{i=1}^n R_i + \sum_{i=1}^n C_i = 3n + 11k + 12(n - k) = 15n - k. \quad \square$$

444 **Lemma 3.12.** *Suppose we have a solution \mathcal{R} of the instance $(\mathcal{C}, \mathcal{P})$ of geometric set cover.*
445 *Then there exists a solution \mathcal{R}' , such that $|\mathcal{R}'| \leq |\mathcal{R}|$, and \mathcal{R}' contains at most one of the*
446 *segments xTrueSegment_i and xFalseSegment_i from each VARIABLE-gadget.*

447 *Proof.* Assume that we have $\{\text{xTrueSegment}_i, \text{xFalseSegment}_i\} \subseteq \mathcal{R}$ for some i . We will show
448 how to modify \mathcal{R} into \mathcal{R}' , such that the number of such i decreases, while \mathcal{R}' is still a valid
449 solution to $(\mathcal{C}, \mathcal{P})$, and $|\mathcal{R}'| \leq |\mathcal{R}|$. Then, by repeating this procedure, we can eventually
450 construct a solution satisfying the property from the Lemma.

451 To construct \mathcal{R}' , we first remove from \mathcal{R} all segments belonging to $\text{segmentsVariable}_i$.
452 Recall that the i -th VARIABLE-gadget corresponds to variable x_i in S . As every variable in
453 S is used in exactly 3 clauses, then one literal x_i or $\neg x_i$ must appear in at least 2 clauses. If
454 that literal is x_i , then we add to the constructed solution all segments from $\text{chooseVariable}_i^{\text{true}}$,
455 otherwise we add all segments from $\text{chooseVariable}_i^{\text{false}}$.

456 Now, there exists at most one CLAUSE-gadget which needs adjustment to make \mathcal{R}' valid;
457 assuming it is the j -th clause, then one of the points $x_{j,0}, y_{j,0}$ or $z_{j,0}$ for this CLAUSE-gadget
458 might be not covered, say $y_{j,0}$. We amend the solution by adding $(y_{j,0}, y_{j,1})$ to \mathcal{R}' .

459 By Lemma 3.4 we know that \mathcal{R} used at least 4 segments from $\text{segmentsVariable}_i$. Therefore,
460 we removed at least 4 segments and added at most 4 segments, so $|\mathcal{R}'| \leq |\mathcal{R}|$. \square

461 **Lemma 3.13.** *Suppose we have a solution \mathcal{R} of the instance $(\mathcal{C}, \mathcal{P})$ of geometric set cover*
462 *that is of size w . Then there exists a solution to S that satisfies at least $15n - w$ clauses.*

463 *Proof.* Let the clauses in S be $c_1, c_2 \dots c_n$ and the variables be $x_1, x_2 \dots x_n$. Given a solution
464 \mathcal{R} of the instance $(\mathcal{C}, \mathcal{P})$ of geometric set cover, we use Lemma 3.12 to modify \mathcal{R} such that
465 for any i it contains at most one of xTrueSegment_i and xFalseSegment_i ; this may decrease the
466 cost of \mathcal{R} , but that does not matter in the subsequent construction. To simplify notation, in
467 the remainder of this proof we use \mathcal{R} to refer to the modified solution.

Given \mathcal{R} , we construct a solution to S by defining an assignment of variables:

$$\phi : \{x_1, x_2 \dots x_n\} \rightarrow \{\text{true}, \text{false}\}$$

468 that satisfies at least $15n - w$ clauses in S .

Definition of ϕ . Recall that due to Lemma 3.12, \mathcal{R} contains at most one of xTrueSegment_i and xFalseSegment_i .

We define the value $\phi(x_i)$ for the variable x_i as follows:

$$\begin{cases} \phi(x_i) = \text{true} & \text{if } \text{xTrueSegment}_i \in \mathcal{R} \\ \phi(x_i) = \text{false} & \text{otherwise} \end{cases}$$

Moreover, from Lemma 3.3 we get $|\text{segmentsVariable}_i \cap \mathcal{R}| \geq 3$ for every i .

Clauses satisfied with the chosen variable assignment. For a clause c_i , \mathcal{R} needs to use at least 11 segments to cover $\text{pointsClause}_i - \{x_{i,0}, y_{i,0}, z_{i,0}\}$ in the i -th CLAUSE-gadget (Lemma 3.9).

Moreover, if none of the points $\{x_{i,0}, y_{i,0}, z_{i,0}\}$ are covered by the segments from $\mathcal{R} \cap \text{segmentsVariable}_i$, then \mathcal{R} needs to cover pointsClause_i with at least 12 segments by Lemma 3.9.

Let us denote a as the amount of such clauses c_i for which none of the points $x_{i,0}, y_{i,0}, z_{i,0}$ in pointsClause_i were covered by segments from $\mathcal{R} \cap \text{segmentsVariable}_j$ for any $1 \leq j \leq n$.

Consider a clause c_i for which at least one of the points $x_{i,0}, y_{i,0}, z_{i,0}$ in pointsClause_i were covered by segments from $\mathcal{R} \cap \text{segmentsVariable}_j$ for some $1 \leq j \leq n$, then denote this point as t and say it corresponds to literal q and variable x_j . Point t can be only covered in $\text{segmentsVariable}_j$ by a corresponding segment xTrueSegment_j or xFalseSegment_j (depending on whether the literal q is negated or not). From the definition of ϕ and the fact that one of this segment is in \mathcal{R} , we know that $\phi(j)$ has the value that evaluates w to be true. Therefore, clause c_i is satisfied.

Consequently, ϕ satisfies all but at most a clauses in S .

To conclude, given a solution to $(\mathcal{C}, \mathcal{P})$ of size w we constructed a variable assignment ϕ that satisfies at least $n - a$ clauses of S . Finally, note that

$$w \geq 3n + 11(n - a) + 12a = 3n + 11n + a = 14n + a,$$

hence

$$15n - w \leq 15n - 14n - a = n - a.$$

Therefore ϕ satisfies at least $15n - w$ clauses of S . □

We are ready to conclude the proof of Lemma 3.1.

Proof of Lemma 3.1. By Lemma 3.11, we know that there exists a solution to $(\mathcal{C}, \mathcal{P})$ of size $15n - k$, so:

$$\text{opt}((\mathcal{C}, \mathcal{P})) \leq 15n - k.$$

Since the optimum solution to S satisfies k clauses, then according to Lemma 3.13:

$$\text{opt}((\mathcal{C}, \mathcal{P})) \geq 15n - k.$$

Therefore, the solution given by Lemma 3.11 of size $15n - k$ is an optimum solution to the instance $(\mathcal{C}, \mathcal{P})$. □

Chapter 4

Fixed-parameter tractable algorithm for geometric set cover problem

In this chapter we show fixed-parameter tractable algorithms for the geometric set cover problem in two different settings. Section 4.1 shows a fixed-parameter tractable algorithm for geometric set cover with unweighted segments. The remainder of the chapter presents a fixed-parameter tractable algorithm for geometric set cover with weighted segments with δ -extension. We show an algorithm for the setting with δ -extension, because the original problem with weights is W[1]-hard, as we show in Chapter 5.

We start with a shared definition for this problem. We define *extreme points* for a set of collinear points.

Definition 4.1. For a set of collinear points C in the plane, **extreme points** of C are the endpoints of the smallest segment that covers all points from set C .

If C consists of one point or is empty, then there are 1 or 0 extreme points respectively.

4.1. Fixed-parameter tractable algorithm for unweighted segments

In this section we consider fixed-parameter tractable algorithms for unweighted geometric set cover with segments. The setting where segments are required to be axis-parallel (or limited to a constant number of directions) has an FPT algorithm already present in literature in the Parametrized Algorithms book [Cygan et al., 2015]. We present an FPT algorithm for geometric set cover with unweighted segments, where segments are in arbitrary directions.

4.1.1. Axis-parallel segments

Theorem 4.1. (*FPT for segment cover with axis-parallel segments*). *There exists an algorithm that given a family \mathcal{P} of axis-parallel segments, a set of points \mathcal{C} and a parameter k , runs in time $\mathcal{O}(2^k)$, and outputs a solution $\mathcal{R} \subseteq \mathcal{P}$ such that $|\mathcal{R}| \leq k$ and \mathcal{R} covers all points in \mathcal{C} , or determines that such a set \mathcal{R} does not exist.*

We present here a simple algorithm from [Cygan et al., 2015] for completeness.

Proof. We show an $\mathcal{O}(2^k)$ -time branching algorithm. In each step, the algorithm selects a point a which is not yet covered, branches to choose one of the two directions, and greedily

chooses a segment a in that direction to cover. This proceeds until either all points are covered or k segments are chosen.

Let us take the point $a = (x_a, y_a)$ which is the smallest among points that are not yet covered in the lexicographic ordering of points in \mathbb{R}^2 . We need to cover a with some of the remaining segments.

Branch over the choice of one of the coordinates (x or y); without loss of generality, let us assume we chose x . Among the segments lying on line $x = x_a$, we greedily add to the solution the one that covers the most points. As a was the smallest in the lexicographical order, all points on the line $x = x_a$ have the y -coordinate larger than y_a . Therefore, if we denote the greedily chosen segment as s , then any other segment on the line $x = x_a$ that covers a can only cover a subset of points covered by s . Thus, greedily choosing s is optimal.

In each step of the algorithm we add one segment to the solution, thus the recursion can be stopped at depth k . If no branch finds a solution, then this means that a solution of size at most k does not exist. \square

Note that the same algorithm can be used for segments in d directions, where we branch over d choices of directions, and it runs in complexity $\mathcal{O}(d^k)$.

4.1.2. Segments in arbitrary directions

In this section we consider the setting where segments are not constrained to a constant number of directions. We present a fixed-parameter tractable algorithm, parameterized by the size of the solution.

Theorem 1.2. (FPT for segment cover). *There exists an algorithm that given a family \mathcal{P} of segments (in any direction), a set of points \mathcal{C} and a parameter k , runs in time $k^{\mathcal{O}(k)}(|\mathcal{C}| \cdot |\mathcal{P}|)^2$, and outputs a solution $\mathcal{R} \subseteq \mathcal{P}$ such that $|\mathcal{R}| \leq k$ and \mathcal{R} covers all points in \mathcal{C} , or determines that such a set \mathcal{R} does not exist.*

We will need the following lemmas proving properties of any instance of the problem.

Lemma 4.1. *Given an instance $(\mathcal{P}, \mathcal{C})$ of the segment cover problem, without loss of generality we can assume that no segment covers a superset of what another segment covers. That is, for any distinct $A, B \in \mathcal{P}$, we have $A \cap \mathcal{C} \not\subseteq B \cap \mathcal{C}$ and $A \cap \mathcal{C} \not\supseteq B \cap \mathcal{C}$.*

Proof. Assume towards a contradiction that there is an instance $(\mathcal{P}, \mathcal{C})$, and two distinct subsets of \mathcal{P} , A, B , such that $A \cap \mathcal{C} \subseteq B \cap \mathcal{C}$.

We construct a set $\mathcal{P}' := \mathcal{P} - \{A\}$. We prove that for any solution \mathcal{R} of $(\mathcal{P}, \mathcal{C})$, we can construct a solution $\mathcal{R}' \subseteq \mathcal{P}'$, such that $|\mathcal{R}'| \leq |\mathcal{R}|$. Let us take any solution \mathcal{R} of $(\mathcal{P}, \mathcal{C})$. If $A \in \mathcal{R}$, then $\mathcal{R}' := \mathcal{R} \cup \{B\} - \{A\}$, otherwise $\mathcal{R}' := \mathcal{R}$. Let us consider the case when $A \in \mathcal{R}$, because the other case is trivial. Since $A \cap \mathcal{C} \subseteq B \cap \mathcal{C}$, then $\mathcal{R} \cup \{B\} - \{A\}$ covers any point from \mathcal{C} that was covered by \mathcal{R} . Also, $|\mathcal{R} \cup \{B\} - \{A\}| \leq |\mathcal{R}|$. \square

Lemma 4.2. *Given an instance $(\mathcal{P}, \mathcal{C})$ of the segment cover problem transformed by Lemma 4.1, if there exists a line L with at least $k + 1$ points on it, then there exists a subset $A \subseteq \mathcal{P}$, of size at most k , such that every solution \mathcal{R} with $|\mathcal{R}| \leq k$ satisfies $|A \cap \mathcal{R}| \geq 1$. Moreover, such a subset can be found in polynomial time.*

Proof. Let us enumerate the points from \mathcal{C} that lie on L as x_1, x_2, \dots, x_t in the order in which they appear on L . Our proposed set is defined as:

$$A := \{\text{segment collinear with } L \text{ that covers } x_i \text{ and does not cover } x_{i-1} : i \in \{1, \dots, k\}\}.$$

561 Where for $i = 1$ we just take a segment that covers x_1 .

562 If such a segment does not exist for any point x as above, then x does not give rise to
 563 any segment in A . We prove the lemma by contradiction. Let us assume that there exists
 564 a solution \mathcal{R} of size at most k such that $\mathcal{R} \cap A = \emptyset$.

565 Let us define a set \mathcal{R}_L , which is defined as segments from \mathcal{R} that are collinear with L .

566 Every segment that is not collinear with L can cover at most one of the points that lie
 567 on this line. Hence, if \mathcal{R}_L was empty, then \mathcal{R} would cover at most k points on line L , but L
 568 had at least $k + 1$ different points from \mathcal{C} on it.

569 Therefore, we know that \mathcal{R}_L is not empty and $|\mathcal{R} - \mathcal{R}_L| \leq k - 1$. Segments from $\mathcal{R} - \mathcal{R}_L$
 570 can cover at most $k - 1$ points among $\{x_1, x_2, \dots, x_k\}$, therefore at least one of these points
 571 must be covered by segments from \mathcal{R}_L . We take the leftmost point from $\{x_1, x_2, \dots, x_k\}$ that
 572 is covered in \mathcal{R}_L and name it a . After the transformation from Lemma 4.1, in \mathcal{R} there is only
 573 one segment that starts in a and is collinear with L , therefore this segment must be in both
 574 \mathcal{R} and A . This contradiction concludes the proof that $|A \cap \mathcal{R}| \geq 1$ for any solution \mathcal{R} of size
 575 at most k . \square

576 We are now ready to prove Theorem 1.2.

577 *Proof of Theorem 1.2.* We will prove this theorem by presenting a branching algorithm that
 578 works in desired complexity. It first branches over the choice of segments to cover the lines
 579 with *many* points and then solves a small instance (where every line has at most k points) by
 580 checking all possible solutions.

581 **Algorithm.** We present a recursive algorithm. Given an instance of the problem:

- 582 (1) Use Lemma 4.1 to remove some redundant segments from our instance.
- 583 (2) If there exists a line with at least $k + 1$ points from \mathcal{C} , we branch over the choice of
 584 adding to the solution one of the at most k possible segments provided by Lemma 4.2;
 585 name this segment s and name the set of points from \mathcal{C} that lie on s as S . By recursion,
 586 we find a solution \mathcal{R} for the instance $(\mathcal{C} - S, \mathcal{P} - \{s\})$, and parameter $k - 1$. We return
 587 $\mathcal{R} \cup \{s\}$. Note that if Lemma 4.2 returned \emptyset , then we respond NO.
- 588 (3) If every line has at most k points on it and $|\mathcal{C}| > k^2$, then answer NO.
- 589 (4) If $|\mathcal{C}| \leq k^2$, solve the problem by brute force: check all subsets of \mathcal{P} of size at most k .

590 **Correctness.** Lemma 4.2 proves that at least one segment that we branch over in (1)
 591 must be present in every solution \mathcal{R} with $|\mathcal{R}| \leq k$. Therefore, the recursive call can find
 592 a solution, provided there exists one.

593 In (2) the answer is no, because every line covers no more than k points from \mathcal{C} , which
 594 implies the same about every segment from \mathcal{P} . Under this assumption we can cover only k^2
 595 points with a solution of size k , which is less than $|\mathcal{C}|$.

596 Checking all possible solutions in (3) is trivially correct.

597 **Complexity.** In the leaves of the recursion we have $|\mathcal{C}| \leq k^2$, so $|\mathcal{P}| \leq k^4$, because
 598 every segment can be uniquely identified by the two extreme points it covers (by Lemma 4.1).
 599 Therefore, there are $\binom{k^4}{k}$ possible solutions to check, each can be checked in time $\mathcal{O}(k|\mathcal{C}|)$.
 600 Thus, (3) takes time $k^{\mathcal{O}(k)}$.

In this branching algorithm our parameter k is decreased with every recursive call, so we have at most k levels of recursion with branching over k possibilities. Candidates to branch over can be found on each level in time $\mathcal{O}((|\mathcal{C}| \cdot |\mathcal{P}|)^{\mathcal{O}(1)})$.

Reduction from Lemma 4.1 can be implemented in time $\mathcal{O}((|\mathcal{C}| \cdot |\mathcal{P}|)^{\mathcal{O}(1)})$.

It follows that the overall complexity is $\mathcal{O}((|\mathcal{C}| \cdot |\mathcal{P}|)^{\mathcal{O}(1)} \cdot k^{\mathcal{O}(k)})$ \square

4.2. Fixed-parameter tractable algorithm for weighted segments with δ -extension

In this section we consider the geometric set cover problem for weighted segments relaxed with δ -extension. We show that this problem admits an FPT algorithm when parameterized by the size of the solution and δ . In the next chapter we show that the assumption about the problem being relaxed with δ -extension is necessary: we prove that geometric set cover problem for weighted segments (without extension) is W[1]-hard, which means there does not exist any FPT algorithm parameterized by solution size for it, assuming $\text{FPT} \neq \text{W}[1]$.

Theorem 1.3. *[FPT for weighted segment cover with δ -extension] There exists an algorithm that given a family \mathcal{P} of n weighted segments (in any direction), a set of m points \mathcal{C} , and parameters k and $\delta > 0$, such that it runs in time $f(k, \delta) \cdot (nm)^c$ for some computable function f and a constant c and outputs a set \mathcal{R} such that:*

- $\mathcal{R} \subseteq \mathcal{P}$,
- $|\mathcal{R}| \leq k$,
- $\mathcal{R}^{+\delta}$ covers all points in \mathcal{C} ,
- the weight of \mathcal{R} is not greater than the weight of an optimum solution of size at most k for this problem without δ -extension

or determines that there is no set \mathcal{R} with $|\mathcal{R}| \leq k$ such that \mathcal{R} covers all points in \mathcal{C} .

To solve this problem we will introduce a lemma about choosing a *dense* subset of points. A dense subset of points for a set of collinear points C and parameters k and δ is a subset of C such that if we cover it with at most k segments, these segments after δ -extension will cover all of the points from C . We will prove that such set of size bounded by some function $f(k, \delta)$ always exists (Lemma 4.3). Later, Lemma 4.3 will allow us to find a kernel for our original problem.

Definition 4.2. For a set of collinear points C , a subset $A \subseteq C$ is (k, δ) -**dense** if for any set of segments R that covers A and such that $|R| \leq k$, it holds that $R^{+\delta}$ covers C .

Lemma 4.3. *For any set of collinear points C , $\delta > 0$ and $k \geq 1$, there exists a (k, δ) -dense set $A \subseteq C$ of size at most $(2 + \frac{2}{\delta})^k$. Moreover, there exists an algorithm that computes the (k, δ) -dense set in time $\mathcal{O}(|C| \cdot (2 + \frac{2}{\delta})^k)$.*

Proof. We prove this for a fixed δ by induction on k .

636 **Inductive hypothesis.** For any set of collinear points C , there exists a set A such that:

- 637 • A is subset of C ,
- 638 • A is (ℓ, δ) -dense for every $1 \leq \ell \leq k$,
- 639 • $|A| \leq (2 + \frac{2}{\delta})^k$,
- 640 • the extreme points of C are in A .

641 **Base case for $k = 1$.** It is sufficient that A consists of the extreme points of C .

642 If they are covered with one segment, it must be a segment that includes the extreme

643 points from C , so it covers the whole set C .

644 There are at most 2 extreme points in C and $2 < 2 + \frac{2}{\delta}$.

645 **Inductive step.** Assuming inductive hypothesis for any set of collinear points C and

646 for parameter k , we will prove it for $k + 1$.

647 Let s be the minimal segment that includes all points from C . That is, the extreme points

648 of C are endpoints of s .

649 We define $M = \lceil 1 + \frac{2}{\delta} \rceil$ subsegments of s by splitting s into M closed segments of equal

650 length. We name these segments v_i , note that $|v_i| = \frac{|s|}{M}$ for each $1 \leq i \leq M$.

651 Let C_i be the subset of C consisting of points lying on v_i .

652 Let t_i be the segment with endpoints being the extreme points of C_i . It might be a

653 degenerate segment if C_i consists of one point, or t_i might be empty if C_i is empty.

654 Figure 4.1 presents an example of such segments v_i and t_i .

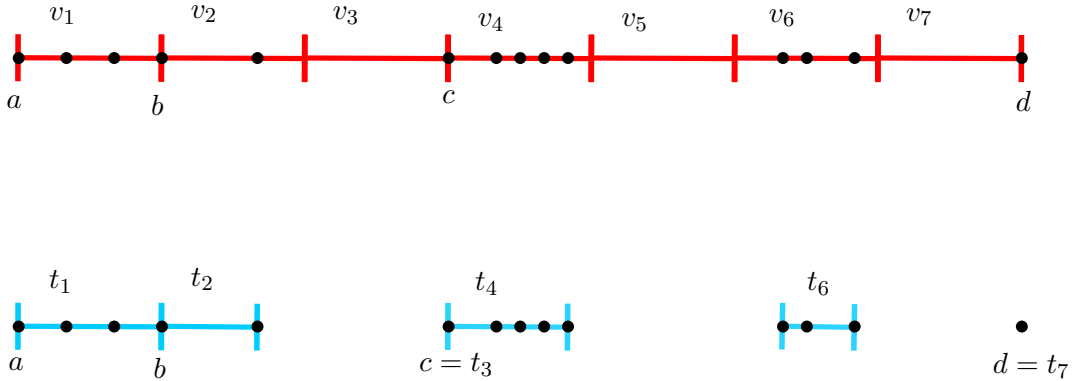


Figure 4.1: **Example of segments v_i and t_i .**

Example for $M = 7$ and some set of points (marked with black circles). The top panel shows segments v_i and the bottom panel shows segments t_i on the same set of points. a and b are the extreme points and therefore segment s ends at a and b . Red segments depict the split into M segments of equal length v_i . Blue segments depict the segments t_i . t_5 is an empty segment, because there are no points that lie on segment v_5 . Segments t_3 and t_7 are degenerated to one point – c and d , respectively. Segments t_1 and t_2 share one point b .

655 We use the inductive hypothesis to choose (k, δ) -dense sets A_i for sets C_i . Note that if

656 $|C_i| \leq 1$, then $A_i = C_i$ and it is still a (k, δ) -dense set for C_i .

657 Then we define $A = \bigcup_{i=1}^M A_i$. Thus A includes the extreme points of C , because they are
 658 included in the sets A_1 and A_M .

The size of each A_i is at most $(2 + \frac{2}{\delta})^k$ from the inductive hypothesis, therefore size of A is at most:

$$M \left(2 + \frac{2}{\delta}\right)^k = \left\lceil 1 + \frac{2}{\delta} \right\rceil \cdot \left(2 + \frac{2}{\delta}\right)^k \leq \left(2 + \frac{2}{\delta}\right)^{k+1}.$$

659 **Proof that A is (k, δ) -dense for C .** Let us take any cover of A with $k + 1$ segments
 660 and call it \mathcal{R} .

661 For every segment t_i , if there exists a segment x in \mathcal{R} that is disjoint with t_i , then we have
 662 a cover of A_i with at most k segments using $\mathcal{R} - \{x\}$. Since A_i is (k, δ) -dense for t_i and C_i ,
 663 $(\mathcal{R} - \{x\})^{+\delta}$ covers C_i . So $\mathcal{R}^{+\delta}$ covers C_i as well.

664 If there exists a segment t_i for which a segment x as defined above does not exist, then
 665 all $k + 1$ segments that cover A_i intersect t_i . An example of such segments is depicted in
 666 Figure 4.2. Let us consider any such t_i . By the inductive hypothesis, the endpoints of s
 667 are in A_1 and A_M respectively, so \mathcal{R} must cover them. For each endpoint of s , there exists
 668 a segment that contains this endpoint and intersects t_i . Let us call these two segments y
 669 and z . It follows that: $|y| + |z| + |t_i| \geq |s|$. Since $|t_i| \leq |v_i| = \frac{|s|}{M} \leq \frac{|s|}{1 + \frac{2}{\delta}} = \frac{|s|\delta}{\delta + 2}$, we have
 670 $\max(|y|, |z|) \geq |s|(1 - \frac{\delta}{\delta + 2})/2 = \frac{|s|}{\delta + 2}$.

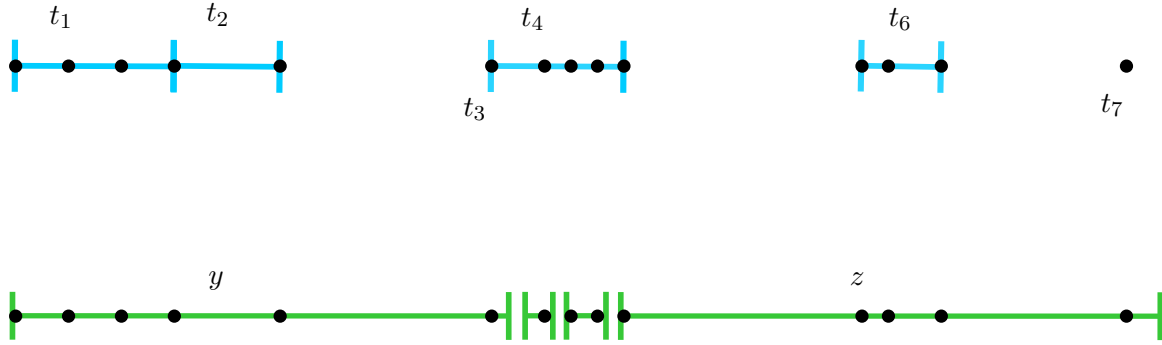


Figure 4.2: **Example of all $k + 1$ segments intersecting one segment t_i .**

Both panels show the same set \mathcal{C} (black circles), the same as in Figure 4.1. The top panel shows blue segments t_i for $M = 7$. The bottom panel shows green segments – solution \mathcal{R} of size 4. All segments from \mathcal{R} intersect t_4 . Segments z and y are named in the figure.

After δ -extension, the longer of these segments will expand at both ends by at least:

$$\max(|y|, |z|)\delta \geq \frac{|s|\delta}{\delta + 2} = \frac{|s|}{1 + \frac{2}{\delta}} \geq \frac{|s|}{M} = |v_i| \geq |t_i|.$$

671 Therefore, the longer of segments y and z will cover the whole segment t_i after δ -extension.
 672 We conclude that $\mathcal{R}^{+\delta}$ covers C_i .

673 Since $C = \bigcup_{i=1}^M C_i$, it follows that $\mathcal{R}^{+\delta}$ covers C .

Algorithm. We can simulate the inductive proof presented above by a recursive algorithm with the following complexity:

$$O\left(|C| + \frac{1}{\delta}\right) + O\left(|C| \cdot \left(2 + \frac{2}{\delta}\right)^k\right).$$

Let us now formulate some claims about the properties for the problem parameterized by the solution size. These properties provide bounds for different objects in the problem instance, which help us to find a small kernel for the problem or conclude that the optimum solution to this instance must be, in terms of size, above some threshold.

Definition 4.3. A line in the plane is **long** if there are at least $k + 1$ points from \mathcal{C} on it.

Claim 4.1. *If there are more than k different long lines, then \mathcal{C} can not be covered with k segments.*

Proof. We prove the claim by contradiction. Let us assume that we have at least $k + 1$ different long lines in our instance of the problem and there is a solution \mathcal{R} of size at most k covering points \mathcal{C} .

Choose any long line L . Every segment from \mathcal{R} which is not collinear with L , covers at most one point that lies on L . L is long, so there are at least $k + 1$ points from \mathcal{C} that lie on L . This implies that there must be a segment in \mathcal{R} that is collinear with L .

Since we have at least $k + 1$ different long lines, there are at least $k + 1$ segments in \mathcal{R} collinear with different lines. This contradicts with the assumption that $|\mathcal{R}| \leq k$. □

Claim 4.2. *If there are more than k^2 points from \mathcal{C} that do not lie on any long line, then \mathcal{C} can not be covered with k segments.*

Proof. We prove the claim by contradiction. Let us assume that we have at least $k^2 + 1$ points from \mathcal{C} that do not lie on any long line, call this set A , and a solution \mathcal{R} of size at most k covering all points in \mathcal{C} .

Every segment s from \mathcal{R} covers at most k points from A . This is because if s covered at least $k + 1$ points from A , then the line in the direction of s would be a long line and that contradicts the definition of A .

If every segment from \mathcal{R} covers at most k points from A and $|\mathcal{R}| \leq k$, then at most k^2 points from A are covered by \mathcal{R} and that contradicts the fact that \mathcal{R} is a solution to the given geometric set cover instance. □

We are now ready to give a proof of Theorem 1.3.

Proof of Theorem 1.3. Our goal is to either answer NO or to find a kernel $(\mathcal{C}', \mathcal{P}')$ of size bounded by $f(k)$ for some function f , such that:

- (*Property 1*) for every solution \mathcal{R} to $(\mathcal{C}, \mathcal{P})$ of size at most k , there exists a set $\mathcal{R}_1 \subseteq \mathcal{P}'$ such that $|\mathcal{R}_1| \leq k$, weight of \mathcal{R}_1 is not greater than weight of \mathcal{R} and \mathcal{R}_1 covers \mathcal{C}' ;
- (*Property 2*) for every set $\mathcal{R}_2 \subseteq \mathcal{P}'$ such that $|\mathcal{R}_2| \leq k$ and \mathcal{R}_2 covers points in \mathcal{C}' , $\mathcal{R}_2^{+\delta}$ covers points in original instance \mathcal{C} .

If we found such sets $(\mathcal{C}', \mathcal{P}')$, using *Property 1* we know that optimum solution of size at most k to $(\mathcal{C}', \mathcal{P}')$ has no greater weight than optimum solution of size at most k to $(\mathcal{C}, \mathcal{P})$. Using *Property 2* we know that any solution to $(\mathcal{C}', \mathcal{P}')$ after δ -extension covers \mathcal{C} .

Therefore finding such sets and solving the instance $(\mathcal{C}', \mathcal{P}')$ by iterating over all of the subsets of \mathcal{P}' of size at most k in desired complexity is sufficient to prove Theorem 1.3.

Definition of \mathcal{C}' and \mathcal{P}' . Let us name the number of different long lines as l . Applying Claims 4.1 and 4.2, if we have more than k different long lines or more than k^2 points from \mathcal{C} that do not lie on any long line, then we answer NO, because these lemmas prove that there is no solution of size at most k to this instance.

Otherwise, we can split \mathcal{C} into at most $k + 1$ sets:

- D : points that do not lie on any long line, $|D| \leq k^2$;
- C_i for $1 \leq i \leq l$: points that lie on the i -th long line, $|C_i| > k$.

Note that sets C_i do not need to be disjoint.

Then, for every set C_i we can use Lemma 4.3 to obtain a (k, δ) -dense set A_i for C_i with $|A_i| \leq (2 + \frac{2}{\delta})^k$.

We define $\mathcal{C}' := D \cup (\bigcup A_i)$. \mathcal{C}' has size at most $k^2 + k(2 + \frac{2}{\delta})^k$. We define \mathcal{P}' as follows: for every pair of points \mathcal{C}' , we choose one segment from \mathcal{P} that has the lowest weight among segments that cover these points or decide that there is no segment that covers them. There are at most $|\mathcal{C}'|^2$ different segments in \mathcal{P}' , therefore both \mathcal{P}' and \mathcal{C}' have size bounded by $\mathcal{O}((k^2 + k(2 + \frac{2}{\delta})^k)^2)$.

Proof of Property 2. First, we prove that for every set $\mathcal{R}_2 \subseteq \mathcal{P}'$ such that $|\mathcal{R}_2| \leq k$ and \mathcal{R}_2 covers points in \mathcal{C}' , $\mathcal{R}_2^{+\delta}$ covers points in the original instance \mathcal{C} .

Let us take such a set \mathcal{R}_2 .

\mathcal{C} is separated into several parts – sets D and C_i . Points from D are covered by \mathcal{R}_2 , because D is part of \mathcal{C}' . Each point from any A_i is covered, because A_i is a part of \mathcal{C}' ; A_i is a (k, δ) -dense set for C_i , therefore $\mathcal{R}_2^{+\delta}$ covers all points in C_i . Therefore, $\mathcal{R}_2^{+\delta}$ covers all points in \mathcal{C} .

Proof of Property 1. Secondly, we prove that for every solution \mathcal{R} to $(\mathcal{C}, \mathcal{P})$ of size at most k , there exists a set $\mathcal{R}_1 \subseteq \mathcal{P}'$ such that $|\mathcal{R}_1| \leq k$ and the weight of \mathcal{R}_1 is not greater than the weight of \mathcal{R} .

For every segment in \mathcal{R} , say s , let us look at the points from \mathcal{C}' that lie on s and call this set of points F . F is of course a set of collinear points. We can cover F with any segment that covers extreme points of F , because all other points lie on the segment between these points. Therefore, we can replace s with a segment s' that has lowest weight among the points that cover the extreme points of F . Such a segment belongs to \mathcal{P}' , because this is how it was defined. Segment s' has weight no greater than the weight of s , because s also covers F .

Therefore, we produced the set \mathcal{R}_1 that has size not greater than size of \mathcal{R} (because some segments s can map to the same segment s'), weight not greater than \mathcal{R} , and it covers \mathcal{C}' .

Complexity We find a solution of $(\mathcal{C}', \mathcal{P}')$ by iterating over all the possible subsets of \mathcal{P}' . Finding sets \mathcal{P}' and \mathcal{C}' and then solving problem for kernel has overall complexity $(|\mathcal{P}| + |\mathcal{C}|)^{\mathcal{O}(1)} \mathcal{O}((2 + \frac{2}{\delta})^k) + \mathcal{O}((k^2 + k(2 + \frac{2}{\delta})^k)^k)$. \square

Chapter 5

W[1]-hardness for axis-parallel weighted segments

In this chapter we consider geometric set cover problem with axis-parallel or right-diagonal weighted segments. In Theorem 1.4 below, we prove that this problem is W[1]-hard when parameterized by the size of the solution.

We believe that the below construction can be improved to only utilize the axis-parallel segments.

Theorem 1.4. *Consider the problem of covering a set \mathcal{C} of points by selecting at most k segments from a set of segments \mathcal{P} with non-negative weights $w : \mathcal{P} \rightarrow \mathbb{R}^+$ so that the weight of the cover is minimal. Then this problem is W[1]-hard when parameterized by k and assuming ETH, there is no algorithm for this problem with running time $f(k) \cdot (|\mathcal{C}| + |\mathcal{P}|)^{o(\sqrt{k})}$ for any computable function f . Moreover, this holds even if all segments in \mathcal{P} are axis-parallel or right-diagonal.*

In order to prove Theorem 1.4 we will show a reduction from a W[1]-hard problem. We introduce the grid tiling problem, which was introduced in [Marx, 2007] (authors call it matrix tiling instead). It was originally described as parameterized problem, but W[1]-hardness follows directly from the theorems stated there. For a more contemporary description of this problem and a proof of W[1]-hardness see Chapter 14 of [Cygan et al., 2015].

Definition 5.1. We define the **powerset** of a set A , denoted as $\text{Pow}(A)$, as the set of all subsets of A , i.e. $\text{Pow}(A) = \{B : B \subseteq A\}$.

Definition 5.2. In the **grid tiling** problem we are given integers n and k , and a function $f : \{1 \dots k\} \times \{1 \dots k\} \rightarrow \text{Pow}(\{1 \dots n\} \times \{1 \dots n\})$ specifying the set of allowed tiles for each cell of a $k \times k$ grid. The task is to decide whether there exist functions $x, y : \{1 \dots k\} \rightarrow \{1 \dots n\}$ that assign colors from $\{1 \dots n\}$ to respectively columns and rows of the grid, so that $(x(i), y(j)) \in f(i, j)$ for all $i, j \in \{1 \dots k\}$.

In short, in the grid tiling problem one needs to assign numbers to rows and columns in such a way that for every pair of a row and a column, the pair of colors assigned to the row and column belongs to the allowed set of tiles for this pair. The next theorem describes the complexity of this problem, which is W[1]-hard when parameterized by the size of the grid.

Theorem 5.1. [Marx, 2007] *Grid tiling is W[1]-hard when parameterized by k and assuming ETH, there is no $f(k) \cdot n^{o(k)}$ -time algorithm solving the grid tiling problem for any computable function f .*

	$x(1) = 3$	$x(2) = 1$	$x(3) = 3$	$x(4) = 7$
$y(4) = 1$	$(\mathbf{2}, \mathbf{1}); (2, 2);$ $(\mathbf{3}, \mathbf{1}); (3, 9)$	$(1, 1); (3, 1)$	$(\mathbf{3}, \mathbf{1}); (7, 2)$	$(\mathbf{2}, \mathbf{1}); (\mathbf{7}, \mathbf{1})$
$y(3) = 1$	$(\mathbf{2}, \mathbf{1}); (\mathbf{3}, \mathbf{1});$ $(4, 2); (8, 2)$	$(1, 1); (1, 3)$	$(\mathbf{3}, \mathbf{1}); (4, 3)$	$(\mathbf{2}, \mathbf{2}); (\mathbf{7}, \mathbf{1})$
$y(2) = 6$	$(\mathbf{2}, \mathbf{6}); (\mathbf{3}, \mathbf{6})$	$(1, 2); (1, \mathbf{6});$ $(2, 6)$	$(2, 6); (\mathbf{3}, \mathbf{6})$	$(\mathbf{2}, \mathbf{6}); (\mathbf{7}, \mathbf{6})$
$y(1) = 4$	$(\mathbf{2}, \mathbf{4}); (2, 6);$ $(\mathbf{3}, \mathbf{4}); (\mathbf{3}, \mathbf{9})$	$(1, 4); (\mathbf{1}, \mathbf{9})$	$(\mathbf{3}, \mathbf{4}); (\mathbf{3}, \mathbf{9})$	$(\mathbf{2}, \mathbf{9}); (\mathbf{7}, \mathbf{4})$

Figure 5.1: **Example of a grid tiling instance and its solution.**

In the first row and column of the table you can see the solution: functions x and y . The tiles used in this solution are marked in **bold**. If we instead chose the tiles marked in **blue** (whenever there is one, taking the tile marked in **bold** otherwise), then that corresponds to setting $x(1) = 2$, and would also form a correct solution. On the other hand, if we instead chose the tiles marked in **red** (as before), then this corresponds to setting $y(1) = 9$ and $x(4) = 2$ and that would **not** form a correct solution. Even though the first row is correct, the cell with coordinates $(3, 4)$ requires tile $(2, 1)$, not $(2, 2)$ (marked in **bold red**).

The remainder of this section is devoted to proving Theorem 1.4 by a reduction from a grid tiling problem instance with parameter k (number of rows in the grid) to a geometric set cover instance with parameter k^2 (size of solution). This reduction is described in Lemma 5.1. This proves the $W[1]$ -hardness of the geometric set cover problem, because if we could solve it with an FPT algorithm, then we could also solve the grid tiling problem (which we reduced to the geometric set cover). Therefore geometric set cover with setting described in Theorem 1.4 is at least as hard as the grid tiling problem.

Let us denote instance of grid tiling problem as (n, k, f) , it consists of:

- the number of colors n ,
- the size of the grid k ,
- the function specifying the allowed tiles $f : \{1, \dots, k\} \times \{1, \dots, k\} \rightarrow \text{Pow}(\{1, \dots, n\} \times \{1, \dots, n\})$.

Let us also define constants:

$$\begin{aligned}\epsilon &:= \frac{1}{2k^2} \\ \delta &:= \frac{1}{4k^4} \\ W_{\text{hv}} &:= 2k^2(n^2 + 1) - 4k^2\epsilon - 4k(1 - \epsilon)\end{aligned}$$

which are going to be used when defining the weight of the constructed instance of geometric set cover with weighted segments.

Lemma 5.1. *Given an instance (n, k, f) of the grid tiling problem, we can construct an instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$ of geometric set cover with weighted segments such that:*

- (1) *if the answer to (n, k, f) is YES, then there exists a solution to $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$ of weight at most $W_{\text{hv}} + k^2\delta$;*

801 (2) if there exists a solution to $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$ of weight at most $W_{\text{hv}} + k^2\delta$, then the
 802 answer to (n, k, f) is YES.

803 First, let us prove Theorem 1.4 using Lemma 5.1.

804 *Proof of Theorem 1.4.* Let us take any instance (n, l, f) of the grid tiling problem. We prove
 805 the theorem by contradiction, therefore we assume that geometric set cover with weighted
 806 segments parameterized by solution size k admits an $n^{o(\sqrt{k})}$ algorithm.

807 Using Lemma 5.1 let us construct an instance I for (n, l, f) . Let us assume that the
 808 optimum solution of size at most k to the instance I has weight w . Using (2) we know that
 809 if $w \leq W_{\text{hv}} + k^2\delta$, then answer to (n, l, f) is YES. If $w > W_{\text{hv}} + k^2\delta$, then using (1) we know
 810 that the answer to (n, l, f) must be NO.

811 Therefore if we could find the solution in time $n^{o(\sqrt{k})}$, then we could solve the grid tiling
 812 problem in $n^{o(l)}$ by constructing an instance of the set cover with weighted segments, solving
 813 it for parameter $k = 3l^2 + 2l$ in time $n^{o(\sqrt{3l^2 + 2l})}$ and then answering based on the weight of
 814 the optimum solution.

815 As $\mathcal{O}(n^{o(l)}) \subseteq \mathcal{O}(n^{o(\sqrt{3l^2 + 2l})})$, existence of this algorithm contradicts Theorem 5.1.

816 Hence such an algorithm can not exist. \square

817 We prove Lemma 5.1 in subsequent sections. First, we define a constructed instance I ,
 818 later property (1) is proved by Lemma 5.2 and property (2) is proved by Lemma 5.6.

819 TODO: Do the same summary of Proofs in chapter 3.

820 Permissive FPT is a relaxed FPT problem, where we need to find solution of any size in
 821 FPT-time, but we compare it to the optimum solution of size at most k . Idea for permissive
 822 FPT in local search was presented in [Marx and Schlotter, 2011], [Gaspers et al., 2012].

823 In the proof of Lemma 5.6 we do not use the assumption that the solution is bounded
 824 by the size, which the problem is parametrized by, $3k^2 + 2k$. If we had a permissive FPT
 825 algorithm, that finds solution of any size that still has weight no more than $W_{\text{hv}} + k^2\delta$, then
 826 we still would have a contradiction with grid tiling being W[1]-hard in proof of Theorem 1.4.
 827 Thus this reduction proves that the problem is not only W[1]-hard, but assuming ETH there
 828 also does not exist permissive FPT algorithm for this problem. Formally we state this in the
 829 Theorem 5.2.

830 **Theorem 5.2. (Permissive FPT does not exist).** Consider the problem of covering a
 831 set \mathcal{C} of points using segments from a set \mathcal{P} with non-negative weights $w : \mathcal{P} \rightarrow \mathbb{R}^+$ so that
 832 the weight of the cover is minimal. Let \mathcal{R}^k be the optimum solution to this problem of size at
 833 most k . The task is to find solution \mathcal{R} of any size such that weight of \mathcal{R} is not greater than
 834 the weight of \mathcal{R}^k .

835 Assuming ETH, there is no algorithm for this problem with running time $f(k) \cdot (|\mathcal{C}| +$
 836 $|\mathcal{P}|)^{o(\sqrt{k})}$ for any computable function f . Moreover, this holds even if all segments in \mathcal{P} are
 837 axis-parallel or right-diagonal.

838 **Construction.** We construct an instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$ of geometric set cover as follows.

839 First, let us choose any bijection $\text{order} : \{1, \dots, n^2\} \rightarrow \{1, \dots, n\} \times \{1, \dots, n\}$.

Define $\text{match}_v(i, j)$ and $\text{match}_h(i, j)$ as boolean functions denoting whether two points
 share x or y coordinate:

$\text{match}_v(i, j)$ is true \iff $\text{order}(i)$ and $\text{order}(j)$ have the same x coordinate,

$\text{match}_h(i, j)$ is true \iff $\text{order}(i)$ and $\text{order}(j)$ have the same y coordinate.

Points. For $1 \leq i, j \leq k$ and $1 \leq t \leq n^2$ define points:

$$h_{i,j,t} := (i \cdot (n^2 + 1) + t, j \cdot (n^2 + 1)),$$

$$v_{i,j,t} := (i \cdot (n^2 + 1), j \cdot (n^2 + 1) + t).$$

Let us define sets H and V as:

$$H := \{h_{i,j,t} : 1 \leq i, j \leq k, 1 \leq t \leq n^2\},$$

$$V := \{v_{i,j,t} : 1 \leq i, j \leq k, 1 \leq t \leq n^2\}.$$

Let us recall that $\epsilon = \frac{1}{2k^2}$. For a point $p = (x, y)$ we define points:

$$p^L := (x - \epsilon, y),$$

$$p^R := (x + \epsilon, y),$$

$$p^U := (x, y + \epsilon),$$

$$p^D := (x, y - \epsilon).$$

Then we define the point set as follows:

$$\mathcal{C} := H \cup \{p^L : p \in H\} \cup \{p^R : p \in H\} \cup V \cup \{p^U : p \in V\} \cup \{p^D : p \in V\}.$$

Definition 5.3. For every point $p \in H$, we name point p^L its **left guard** and point p^R its **right guard**.

Similarly for every points $p \in V$, we name point p^D its **lower guard** and point p^U its **upper guard**.

Segments. For $1 \leq i, j \leq k$ and $1 \leq t, t_1, t_2 \leq n^2$ define segments:

$$\text{hor}_{i,j,t_1,t_2} := (h_{i,j,t_1}^R, h_{i+1,j,t_2}^L),$$

$$\text{ver}_{i,j,t_1,t_2} := (v_{i,j,t_1}^U, v_{i,j+1,t_2}^D),$$

$$\text{horBeg}_{i,t} := (h_{1,i,1}^L, h_{1,i,t}^L),$$

$$\text{horEnd}_{i,t} := (h_{k,i,t}^R, h_{k,i,n^2}^R),$$

$$\text{verBeg}_{i,t} := (v_{i,1,1}^D, v_{i,1,t}^D),$$

$$\text{verEnd}_{i,t} := (v_{i,k,t}^U, v_{i,k,n^2}^U).$$

Next, we define sets of vertical and horizontal segments:

$$\begin{aligned} \text{HOR} &:= \{\text{hor}_{i,j,t_1,t_2} : 1 \leq i < k, 1 \leq j \leq k, 1 \leq t_1, t_2 \leq n^2, \text{match}_h(t_1, t_2) \text{ holds}\} \\ &\cup \{\text{horBeg}_{i,t} : 1 \leq i \leq k, 1 \leq t \leq n^2\} \\ &\cup \{\text{horEnd}_{i,t} : 1 \leq i \leq k, 1 \leq t \leq n^2\}, \end{aligned}$$

$$\begin{aligned} \text{VER} &:= \{\text{ver}_{i,j,t_1,t_2} : 1 \leq i \leq k, 1 \leq j < k, 1 \leq t_1, t_2 \leq n^2, \text{match}_v(t_1, t_2) \text{ holds}\} \\ &\cup \{\text{verBeg}_{i,t} : 1 \leq i \leq k, 1 \leq t \leq n^2\} \\ &\cup \{\text{verEnd}_{i,t} : 1 \leq i \leq k, 1 \leq t \leq n^2\}. \end{aligned}$$

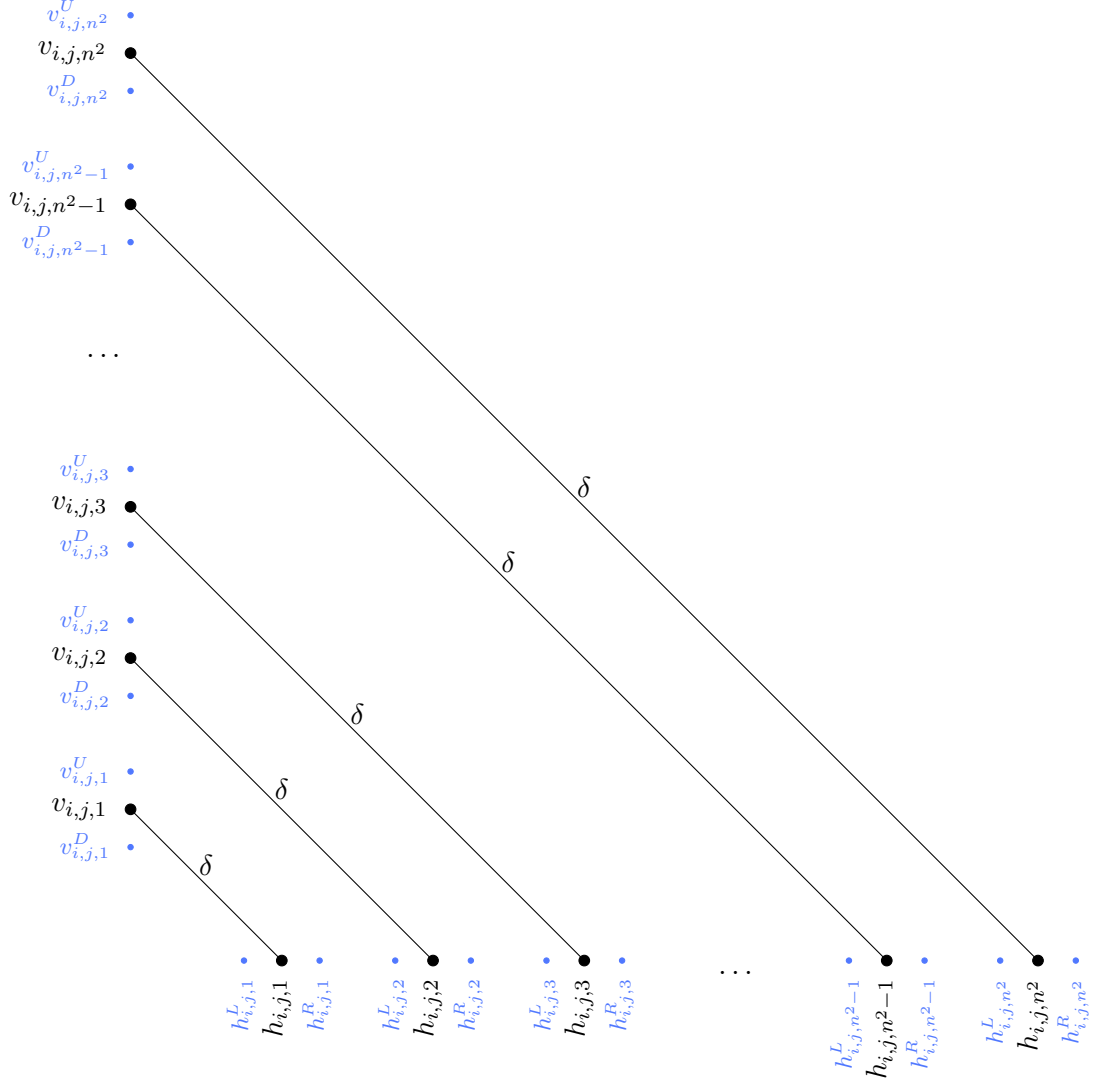


Figure 5.2: **Vertices and segments in DIAG.**

This is an example of constructed points any $1 \leq i, j \leq k$. Points from H and V are marked in black, their guards are marked in blue. You can also see segments from DIAG with their weights (equal to δ).

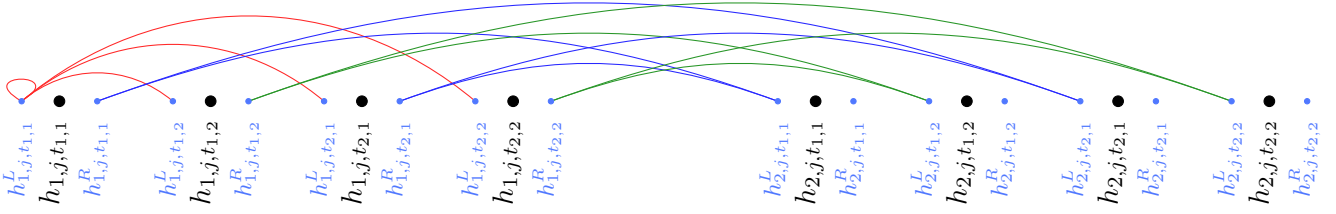


Figure 5.3: **Vertices and segments in HOR.**

This is an example for $n = 2$ and any $1 \leq j \leq k$. Points from H are marked in black, their guards are marked in light blue. $t_{i,j}$ is a notation that we use for $\text{order}^{-1}(i, j)$. Segments are represented as arcs between endpoints. You can see $\text{horBeg}_{j,t}$ segments in red. $\text{horBeg}_{j,1}$ is degenerated to a single point at $h_{1,1,t_{1,1}}^L$. Segments $\text{hor}_{i,j,t_{x_1,y},t_{x_2,y}}$ are marked in blue and green. Blue segments connect $t_{x_1,y}$ and $t_{x_2,y}$ such that they share y-coordinate equal to 1, for green segments it is equal to 2.

847 An example is depicted in Figure 5.3.

Finally, we also define a set of right-diagonal segments:

$$\text{DIAG} := \{(h_{i,j,t}, v_{i,j,t}) : 1 \leq i, j \leq k, 1 \leq t \leq n^2, \text{order}(t) \in f(i, j)\}.$$

848 An example of such segments is depicted in Figure 5.2.

849 Every segment in **DIAG** connects points $(i(n^2+1)+t, j \cdot (n^2+1))$ and $(i \cdot (n^2+1), j(n^2+1) + t)$
 850 for some $1 \leq i, j \leq k, 1 \leq t \leq n^2$. The line on which it lies can be described by linear equation
 851 $x + y = t + (i + j)(n^2 + 1)$, thus these segments are in fact right-diagonal.

852 The constructed segment set is defined as:

$$\mathcal{P} := \text{HOR} \cup \text{VER} \cup \text{DIAG}.$$

853 The weight of each segment in $\text{HOR} \cup \text{VER}$ is equal to its length, while every segment in
 854 **DIAG** has weight δ .

$$w(s) = \begin{cases} \text{length}(s) & \text{if } s \in \text{HOR} \cup \text{VER} \\ \delta & \text{if } s \in \text{DIAG} \end{cases}$$

855 Now, we prove that the constructed instance of geometric set cover with weighted segments
 856 indeed gives a correct and sound reduction of the grid tiling problem. Lemma 5.2 proves that
 857 if a solution to the instance of the grid tiling instance exists, then there exists a solution with
 858 suitably bounded size and weight of the constructed instance of geometric set cover. Then
 859 Lemma 5.6 proves that if there is a solution to the geometric set cover instance with bounded
 860 weight, then there exists a solution to the original grid tiling instance.

861 **Lemma 5.2.** *If there exists a solution to the grid tiling instance $(f_{i,j})$, then there exists*
 862 *a solution to the instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$ of geometric set cover with weight $W_{\text{hv}} + k^2\delta$.*

863 *Proof.* Suppose there exists a solution x, y of the instance $(f_{i,j})$ of the grid tiling problem.

864 We define the proposed solution $\mathcal{R} \subseteq \mathcal{P}$ of the instance of geometric set cover in three

parts: $D \subseteq \text{DIAG}$, $A \subseteq \text{HOR}$ and $B \subseteq \text{VER}$:

$$\begin{aligned}
D &:= \{(v_{i,j,t}, h_{i,j,t}) : 1 \leq i, j \leq k, t = \text{order}^{-1}(x(i), y(j))\}, \\
A &:= \{\text{horBeg}_{i, \text{order}^{-1}(x(1), y(i))} : 1 \leq i \leq k\} \\
&\cup \{\text{horEnd}_{i, \text{order}^{-1}(x(k), y(i))} : 1 \leq i \leq k\} \\
&\cup \{\text{hor}_{i,j, \text{order}^{-1}(x(i), y(j)), \text{order}^{-1}(x(i+1), y(j))} : 1 \leq i < k, 1 \leq j \leq k\}, \\
B &:= \{\text{verBeg}_{i, \text{order}^{-1}(x(i), y(1))} : 1 \leq i \leq k\} \\
&\cup \{\text{verEnd}_{i, \text{order}^{-1}(x(i), y(k))} : 1 \leq i \leq k\} \\
&\cup \{\text{ver}_{i,j, \text{order}^{-1}(x(i), y(j)), \text{order}^{-1}(x(i), y(j+1))} : 1 \leq i \leq k, 1 \leq j < k\}, \\
\mathcal{R} &:= D \cup A \cup B.
\end{aligned}$$

Since $\mathcal{C} = H \cup V$, we show that \mathcal{R} covers the whole set H ; the proof for V is analogous.

Fix any $1 \leq j \leq k$ and define $t_i := \text{order}^{-1}(x(i), y(j))$. The two leftmost segments in A for this j are $\text{horBeg}_{j,t_1} = (h_{1,j,1}^L, h_{1,j,t_1}^L)$ and $\text{hor}_{1,j,t_1,t_2} = (h_{1,j,t_1}^R, h_{2,j,t_2}^L)$. Therefore, points $h_{1,j,x}, h_{1,j,x}^L$ and $h_{1,j,x}^R$ for all $1 \leq x \leq n^2$ are covered by horBeg_{j,t_1} and hor_{1,j,t_1,t_2} , excluding point h_{1,j,t_1} .

Analogously for $2 \leq i \leq k-1$, the two consecutive segments $\text{hor}_{i-1,j,t_{i-1},t_i}$ and $\text{hor}_{i,j,t_i,t_{i+1}}$ cover points $h_{i,j,x}, h_{i,j,x}^L$ and $h_{i,j,x}^R$ for all $1 \leq x \leq n^2$, excluding point h_{i,j,t_i} .

Finally $\text{hor}_{k-1,j,t_{k-1},t_k}$ and horEnd_{j,t_k} cover all points $h_{k,j,x}, h_{k,j,x}^L$ and $h_{k,j,x}^R$ for $1 \leq x \leq n^2$, excluding point h_{k,j,t_k} .

D covers all points h_{i,j,t_i} and v_{i,j,t_i} . As j was chosen arbitrarily, all points in H are covered. The size of this proposed solution is:

$$|\mathcal{R}| = |D| + |A| + |B| = k^2 + (k+1)k + (k+1)k = 3k^2 + 2k.$$

Then, we need to compute the total weight of the solution \mathcal{R} . First, we compute the sum of weights of segments in A . Fix $1 \leq j \leq k$ and consider segments collinear with the j -th horizontal line. All points $h_{i,j,t}, h_{i,j,t}^L$ and $h_{i,j,t}^R$ for every $1 \leq i \leq k$ and $1 \leq t \leq n^2$ are covered by A excluding points $h_{i,j, \text{order}^{-1}(x(i), y(j))}$. Every such point leaves a gap of length 2ϵ between $h_{i,j, \text{order}^{-1}(x(i), y(j))}^L$ and $h_{i,j, \text{order}^{-1}(x(i), y(j))}^R$. Therefore, the total weight of segments in A that lie on the line in question equals the length of the segment $(h_{1,1,1}^L, h_{i,k,n^2}^R)$ minus $2\epsilon k$, which is $k(n^2 + 1) - 2(1 - \epsilon) - 2k\epsilon$. We need to multiply that by k , as we consider all possible values of j .

Computation for vertical segments is analogous and yields the same result. Every segment in D has weight δ , therefore the sum of all weights is equal to:

$$2k(k(n^2 + 1) - 2(1 - \epsilon) - 2k\epsilon) + k^2\delta = W_{\text{hv}} + k^2\delta.$$

□

Now we present a few additional properties of the constructed instance of the geometric set cover that help us to prove Lemma 5.6.

Claim 5.1. *In any solution to the instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$:*

- *the left and right guards of points in H (points in $\{p^L : p \in H\} \cup \{p^R : p \in H\}$) have to be covered with segments from HOR ,*
- *the lower and upper guards of points in V (points in $\{p^D : p \in V\} \cup \{p^U : p \in V\}$) have to be covered with segments from VER .*

Proof. We prove the claim for the points from H as the proof for points from V is analogous. Every segment in **VER** is vertical and has x-coordinate equal to $i(n^2+1)$ for some $1 \leq i \leq k$, so they all have different x-coordinate than any left or right guard of points in H .

For every point x which is a left or right guard of a point in H , there are kn^2 segments from **DIAG** that intersect with the horizontal line that goes through x . All of these segments intersect with this line in points from set H , therefore none of them covers any of the guards.

Therefore none of the segments from **VER** or **DIAG** covers any of the guards of the points in H . \square

Claim 5.2. *For any $1 \leq i, j \leq n$ and any solution to the instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$, all but at most one point $h_{i,j,t}$ and at most one point $v_{i,j,t}$ for $1 \leq t \leq n^2$ must be covered with segments from **HOR** or **VER**.*

Proof. We prove the claim for horizontal segments, as the proof for vertical segments is analogous.

We prove this by contradiction. Assume that we have two points $h_{i,j,t_1}, h_{i,j,t_2}, 1 \leq t_1 < t_2 \leq n^2$, such that they are not covered with segments from **HOR**.

Point h_{i,j,t_1}^R has to be covered with a segment from **HOR** by Claim 5.1. Every segment in **HOR** covering h_{i,j,t_1}^R , but not h_{i,j,t_1} must start at h_{i,j,t_1}^R and all such segments cover also h_{i,j,t_2} . This contradicts the assumption, which concludes the proof. \square

Lemma 5.3. *For every solution \mathcal{R} to the instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$, the sum of weights of segments chosen from sets **HOR** and **VER** is at least W_{hv} .*

Proof. Let us fix $1 \leq i \leq k$.

We provide a lower bound for the sum of lengths of vertical segments from $\mathcal{R} \cap \text{VER}$. This bound is the same for each i and is the same for horizontal lines, thus we need to multiply such a bound by $2k$.

(1) The total length between $v_{i,1,1}^D$ and v_{i,k,n^2}^U is:

$$(k(n^2 + 1) + n^2 + \epsilon) - ((n^2 + 1) + 1 - \epsilon) = k(n^2 + 1) - 2(1 - \epsilon).$$

(2) For every $1 \leq j \leq k$ there exists at most one $1 \leq t \leq n^2$ such that $v_{i,j,t}$ is not covered by segments from **VER** (Claim 5.2). Its guards (see Definition 5.3) $v_{i,j,t}^U$ and $v_{i,j,t}^D$ have to be covered in **VER** (Claim 5.1). Therefore, at most k spaces of length 2ϵ can be left not covered by segments from **VER** between $v_{i,1,1}^D$ and v_{i,k,n^2}^U .

The sum of these lower bounds for vertical and horizontal lines is:

$$2k(k(n^2 + 1) - 2k\epsilon - 2(1 - \epsilon)) = 2k^2(n^2 + 1) - 4k^2\epsilon - 4k(1 - \epsilon) = W_{\text{hv}}.$$

\square

Lemma 5.4. *Let \mathcal{R} be a solution to a constructed instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$ with weight at most $W_{\text{hv}} + k^2\delta$. Then for every $1 \leq i, j \leq k$ there exists $1 \leq t \leq n^2$ such that:*

- (1) $v_{i,j,t}, h_{i,j,t}$ are not covered by segments from **VER** or **HOR**;
- (2) segment $(v_{i,j,t}, h_{i,j,t})$ is in solution \mathcal{R} ;
- (3) $\text{order}(t) \in f(i, j)$, that is, $\text{order}(t)$ is an allowed tile for (i, j) ;

928 (4) for every $1 \leq s \leq n^2$, $s \neq t$, $v_{i,j,s}$ is covered in **VER**;

929 (5) for every $1 \leq s \leq n^2$, $s \neq t$, $h_{i,j,s}$ is covered in **HOR**.

930 *Proof.* At most one of the points $\{h_{i,j,t_x} : 1 \leq t_x \leq n^2\}$ and one of the points $\{v_{i,j,t_y} : 1 \leq$
 931 $t_y \leq n^2\}$ is covered with **DIAG** (Claim 5.2).

932 Moreover, exactly one such point h_{i,j,t_x} and one such point v_{i,j,t_y} is covered with **DIAG**,
 933 because if none of them were covered, then the solution would have to have weight at least
 934 $W_{\text{hv}} + 2\epsilon$ (see the proof of Lemma 5.3), which is more than $W_{\text{hv}} + k^2\delta$.

935 We observe that points h_{i,j,t_x} and v_{i,j,t_y} have to be covered with the same segment from
 936 **DIAG**. Indeed we need to use at least k^2 of them to use exactly one **DIAG** segment for every
 937 pair of $1 \leq i, j \leq k$, if we used 2 segments from **DIAG** for one pair (i, j) , then we would have
 938 used total weight at least $W_{\text{hv}} + k^2\delta + \delta$ (Lemma 5.3), which is more than $W_{\text{hv}} + k^2\delta$. Since
 939 points h_{i,j,t_x} and v_{i,j,t_y} are covered by a single segment from **DIAG**, we have $t_x = t_y$.

940 Therefore $t_x = t_y$ and $\text{order}(t_x)$ is an allowed tile for (i, j) because the corresponding
 941 segment is in **DIAG**. \square

942 We refer to the function mapping $1 \leq x \leq k$ to t_x from Lemma 5.4 as **diagonal** : $\{1 \dots k\} \times$
 943 $\{1 \dots k\} \rightarrow \{1 \dots n^2\}$.

944 **Lemma 5.5.** *Let \mathcal{R} be any solution of a constructed instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$ with weight*
 945 *at most $W_{\text{hv}} + k^2\delta$. Then:*

946 1. for any $1 \leq i < k, 1 \leq j \leq k$, $\text{match}_h(\text{diagonal}(i, j), \text{diagonal}(i + 1, j))$ is **true**;

947 2. for any $1 \leq i \leq k, 1 \leq j < k$, $\text{match}_v(\text{diagonal}(i, j), \text{diagonal}(i, j + 1))$ is **true**.

948 *Proof.* We prove (1) by contradiction, the proof of (2) is analogous.

949 Let us take any $1 \leq i < k, 1 \leq j \leq k$ and name $t_1 = \text{diagonal}(i, j)$ and $t_2 = \text{diagonal}(i +$
 950 $1, j)$. We also assume that $\text{match}_h(t_1, t_2)$ is **false**, which is equivalent to the fact that segment
 951 $(h_{i,j,t_1}^R, h_{i+1,j,t_2}^L)$ is not in set **HOR**.

952 Therefore h_{i,j,t_1} and h_{i+1,j,t_2} are not covered by segments from **HOR** (Lemma 5.4), while
 953 h_{i,j,t_1}^R and h_{i+1,j,t_2}^L have to be covered by segments from **HOR** (Claim 5.1).

954 Every segment from **HOR** either:

955 • starts at point h_{x,y,z_1}^R and ends at point h_{x+1,y,z_2}^L for some $1 \leq x < k, 1 \leq y \leq k$ and
 956 $1 \leq z_1, z_2 \leq n^2$;

957 • is **horBeg** _{y,z} and starts at $h_{1,y,1}^L$ and ends at $h_{1,y,z}^L$ for some $1 \leq y \leq k$ and $1 \leq z \leq n^2$;

958 • is **horEnd** _{y,z} and starts at $h_{k,y,z}^R$ and ends at h_{k,y,n^2}^R for some $1 \leq y \leq k$ and $1 \leq z \leq n^2$.

959 All of the points between h_{i,j,t_1}^R and h_{i+1,j,t_2}^L are covered by segments in **HOR** and there is no
 960 segment $(h_{i,j,t_1}^R, h_{i+1,j,t_2}^L)$ in **HOR**. Hence, there are at least two different segments covering
 961 them. If both of these segments are neither **horBeg** _{y,z} nor **horEnd** _{y,z} , then one of them must
 962 begin at h_{i,j,t_1}^R and end at h_{i+1,j,t_2}^L and there must be other one that begins at h_{i,j,z_1}^R and ends
 963 at h_{i+1,j,t_2}^L for some $1 \leq z_1, z_2 \leq n^2$.

964 Thus, the space between h_{i,j,z_1}^R and h_{i+1,j,t_2}^L would be covered twice and is longer than
 965 ϵ . The case when one of them is **horBeg** _{y,z} or **horEnd** _{y,z} is analogous. They can't be both
 966 **horBeg** _{y,z} or **horEnd** _{y,z} .

967 By the proof of Lemma 5.3, the lower bound for weight of such a solution is $W_{\text{hv}} + \epsilon$ which
 968 is more than $W_{\text{hv}} + k^2\delta$.

969 Therefore h_{i,j,t_1}^R and h_{i+1,j,t_2}^L must be covered by one segment from **HOR**, namely $(h_{i,j,t_1}^R, h_{i+1,j,t_2}^L)$.

970 Hence $(h_{i,j,t_1}^R, h_{i+1,j,t_2}^L)$ is a segment in **HOR** and $\text{match}_h(t_1, t_2)$ is **true**. \square

971 **Lemma 5.6.** *If there exists a solution to instance $(\mathcal{C}, \mathcal{P}, w, 3k^2 + 2k)$ with weight at most*
 972 *$W_{\text{hv}} + k^2\delta$, then there exists a solution to the grid tiling instance $(f_{i,j})$.*

973 *Proof.* Take `diagonal` function from Lemma 5.4.

974 To define the x function for every $1 \leq i \leq k$ set $x(i) := x_i$ where $(x_i, a) = \text{order}(v_{i,1})$.
 975 Similarly, to define the y function, for every $1 \leq i \leq k$ set $y(i) := y_i$ where $(b, y_i) = \text{order}(h_{1,i})$

976 To prove that this is a correct solution to grid tiling, we need to prove that for every
 977 $1 \leq i, j \leq k$, $(x(i), y(j))$ is in the allowed tiles set $f(i, j)$.

978 Let us take any $1 \leq i, j \leq k$. By Lemma 5.5 and simple induction, we know that
 979 `matchh(diagonal(1, j), diagonal(i, j))` and `matchv(diagonal(i, 1), diagonal(i, j))` are `true`. There-
 980 fore `order(diagonal(i, j)) = (x(i), y(j))`. By Lemma 5.4 we know that `order(diagonal(i, j))` is in
 981 $f(i, j)$. Therefore $(x(i), y(j))$ is in $f(i, j)$. \square

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