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Approximation and Parametrized Algorithms for Segment Set Cover

6

Master's thesis

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in COMPUTER SCIENCE

8

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9

June 2020

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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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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34 D.127.6. Numerical blabalysis

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Tytuł pracy w języku polskim

36 Algorytmy parametryzowania i trudność aproksymacji problemu pokrywania zbiorów
37 odcinkami na płaszczyźnie

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Chapter 1

Introduction

The Set Cover problem is one of the most common NP-complete problems. [tutaj referencja]
We are given a family of sets and have to choose the smallest subfamily of these sets that cover
all their elements. This problem naturally extends to settings where we put different weights
on the sets and look for the subfamily of the minimal weight. This problem is NP-complete
even without weights and if we put restrictions on what the sets can be. One of such variants
is Vertex Cover problem, where sets have size 2 (they are edges in a graph).

In this work we focus on another such variant where the sets correspond to some geometric
shapes and only some points of the plane have to be covered. When these shapes are rectangles
with edges parallel to the axis, the problem can be proven to be W[1]-complete (solution of
size k cannot be found in $n^o(k)$ time), APX-complete (for sufficiently small $\epsilon > 0$, the problem
does not admit $1 + \epsilon$ -approximation scheme) [referencje].

Some of these settings are very easy. Set cover with lines parallel to one of the axis can
be solved in polynomial time.

There is a notion of δ -expansions, which loosen the restrictions on geometric set cover. We
allow the objects to cover the points after δ -expansion and compare the result to the original
setting. This way we can produce both FPT and EPTAS for the rectangle set cover with
 δ -extensions [referencje].

Our contribution. In this work, we prove that unweighted geometric set cover with seg-
ments is fixed parameter tractable (FPT).

Moreover, we show that geometric set cover with segments is APX-complete for unweighted
axis-parallel segments, even with $1/2$ -extensions. So the problem for very thin rectangles
also can't admit PTAS. Therefore, in the efficient polynomial-time approximation scheme
(EPTAS) for *fat polygons* by [Har-Peled and Lee, 2009], the assumption about polygons
being fat is necessary.

Finally, we show that geometric set cover with weighted segments in 3 directions is
W[1]-complete. However, geometric set cover with weighted segments is FPT if we allow
 δ -extension.

This result is especially interesting, since it's counter-intuitive that the unweighted setting
is FPT and the weighted setting is W[1]-complete. Most of such problems (like vertex cover
or [wiecej przykladow]) are equally hard in both weighted and unweighted settings.

100 Chapter 2

101 Definitions

102 Some definitions what geometric set cover is. \mathcal{P} – set of objects, \mathcal{C} – set of points. Choose
103 $\mathcal{R} \subset \mathcal{P}$ such that every point in \mathcal{C} is inside some element from \mathcal{R} and $|\mathcal{R}|$ is minimal.

104 In parametrized setting we only look among $|\mathcal{R}| \leq k$. In weighted settings there is some
105 $f : \mathcal{P} \rightarrow \mathbb{R}$ and we minimize $\sum_{R \in \mathcal{R}} f(R)$.

106 Chapter 3

107 Geometric Set Cover with segments

108 3.1. FPT for segments

109 3.1.1. Segments parallel to one of the axis

110 You can find this in Platypus book.

111 We'll show $\mathcal{O}(2^k)$ branching algorithm. Let's take point K that hasn't been covered yet
112 with the smallest coordinate in lexicographical order. We need to cover K with some of the
113 remaining segments.

114 We choose one of the 2 directions on which we will cover this point. In this direction
115 we take greedily the segment that will cover the most points (there are points in \mathcal{C} only on
116 one side of K in this direction, so all segments covering K in this direction create monotone
117 sequence of sets – zbiory zstępujące).

118 3.1.2. Segments in d directions

119 The same algorithm as before but in complexity $\mathcal{O}(d^k)$.

120 3.1.3. Segments in arbitrary direction

121 **Theorem 3.1.1 (FPT for segment cover).** *There exists an algorithm that given a family*
122 *\mathcal{P} of n segments (in any direction), a set of m points \mathcal{C} and a parameter k , runs in time*
123 *$f(k) \cdot (nm)^c$ for some computable function f and constant c , and outputs a subfamily $\mathcal{R} \subseteq \mathcal{P}$*
124 *such that $|\mathcal{R}| \leq k$ and \mathcal{R} covers all points in \mathcal{C} .*

125 **Proof.** We will show such algorithm in FPT.

126 If there exist two segments a and b in \mathcal{P} , such that any point covered by a is also covered
127 by b , then without loss of generality we can remove segment a from \mathcal{P} . We repeat this process
128 until no such (a, b) pair exists.

129 Let us first assume that we reduced our instance to a kernel, where *any line* contains no
130 more than k points.

131 Since any segment covers a set of colinear points, for such a kernel k segments can cover
132 only at most k^2 points. Therefore, for the answer to be positive, the number of points has
133 to be at most k^2 . The number of segments is now bounded by k^4 , since if we consider two
134 *extreme* points covered by a given segment, then these pairs must be distinct, otherwise two
135 segments would contain the same set of points. Since both the number of points and the

number of segments is bounded by a function of k , this instance can be easily solved in time $O(f(k))$.

It remains to show how to construct the kernel.

Assume there exists a line l containing points x_1, \dots, x_t , where $t \geq k + 1$. Note that a segment that does not lie on l can cover only at most one of the points x_i . Therefore, out of points x_1, \dots, x_{k+1} , at least one has to be covered by a segment that lies on l , let us fix x_i to be the first such point. Then, we can greedily choose a segment that lies on l , covers x_i , and also covers the largest number of points x_j for $j > i$.

Since we have at most $k + 1$ choices to branch over and each choice adds a segment to the constructed solution, we obtain an algorithm with complexity $O(k^k)$.

3.2. APX-completeness for segments parallel to axis

Let's analyze approximation of set cover with rectangles.

The question on the table is if there exists $(1 + \epsilon)$ -approximation scheme for set cover with rectangles.

Let's restrict this problem to some very easy setting: segments parallel to axes and allow $(1/2)$ -extension. Segments are basically degenerated rectangles with one side very narrow.

Theorem 3.2.1 (*axis-parallel segment set cover with $1/2$ -extension is APX-hard*). For sufficiently small $\epsilon > 0$, there does not exist an $(1 + \epsilon)$ -approximation scheme for unweighted geometric set cover with axis-parallel segments in 2D (even with $1/2$ -extension) (problem is APX-hard).

Theorem 3.2.2 (*rectangle set cover is APX-hard*). For sufficiently small $\epsilon > 0$, there does not exist an $(1 + \epsilon)$ -approximation scheme for unweighted geometric set cover with rectangles (even with $1/2$ -extension) (problem is APX-hard).

The problem of rectangle set cover doesn't have $(1 + \epsilon)$ -approximation scheme even in the setting with segments parallel to axis with $1/2$ -extensions. Theorem 3.2.1 implies Theorem 3.2.2.

We will prove it by taking a problem that is APX-complete (doesn't have $(1 + \epsilon)$ -approximation scheme). Such problem in this section will be MAX-(3,3)-SAT that we will define in detail below.

Given an instance I of MAX-(3,3)-SAT, we will construct an instance J of axis-parallel segment set cover problem, such that $(1 + c \cdot \epsilon)$ -approximation of J will approximate an I with $(1 + \epsilon)$ scheme for some constant $c > 1$. Therefore if there would exist general approximation scheme of the axis-parallel segment set cover problem, we would produce a general approximation scheme for MAX-(3,3)-SAT (that doesn't exist).

3.2.1. Definition of MAX-(3,3)-SAT problem

MAXSAT problem is an optimization problem. We are given 3-CNF formula and we find assignment that satisfies the most clauses in a formula.

MAX-(3,3)-SAT problem is a MAXSAT problem with additional restriction, that every variable appears in exactly 3 clauses, so the number of clauses is equal to number of variables.

In the lemmas above we use a property of this problem proved in [Håstad, 2001] and described in Theorem 3.2.3.

177 **Theorem 3.2.3 [Håstad, 2001]**

178 *For any $\epsilon > 0$, it is NP-hard to distinguish satisfiable $(3,3)$ -SAT formulas from*
 179 *$(7/8 + \epsilon)$ -satisfiable $(3,3)$ -SAT formulas. Said equivalently, MAX- $(3,3)$ -SAT is nonapprox-*
 180 *imable beyond the random assignment threshold on satisfiable instances.*

181 **Lemma 3.2.1** *Given an instance of MAX- $(3,3)$ -SAT with n variables and optimal result k ,*
 182 *we can construct an instance of axis-parallel segments in 2D, which optimal result (even with*
 183 *$1/2$ -extension) is exactly $15n - k$.*

184 We will provide a proof for Lemma in subsequent sections, but meanwhile let's prove
 185 Theorem 3.2.1 using Lemma 3.2.1 and Theorem 3.2.3.

186 **Proof of Theorem 3.2.1** Take any $0 < \epsilon < 1/(15 \cdot 8)$.

187 Let's assume that there exists an $(1 + \epsilon)$ -approximation scheme for unweighted geometric
 188 set cover with axis-parallel segments in 2D. We will construct an algorithm distinguishing
 189 instances of MAX- $(3,3)$ -SAT in Theorem 3.2.3. Take an instance S of $(3,3)$ -SAT to be distin-
 190 guished and construct an instance of geometric set cover using Lemma 3.2.1, name it I .

191 Use $(1 + \epsilon)$ -approximation scheme for instances of geometric set cover, let's name the result
 192 of this approximation for an instance of problem I as $approx(I)$.

193 We will prove that if $approx(I) \geq 15n - (\frac{7}{8} + \epsilon)n$ then S satisfied at most $(\frac{7}{8} + \epsilon)n$ clauses
 194 and if $approx(I) < 15n - (\frac{7}{8} + \epsilon)n$ then S was satisfiable.

Assume S satisfiable From definition of satisfiable S we have:

$$OPT(S) = n$$

195 From Lemma 3.2.1 we have:

$$OPT(I) = 14n$$

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

Assume S at most $(\frac{7}{8} + \epsilon)n$ satisfiable From definition of satisfiable S we have:

$$OPT(S) \leq (\frac{7}{8} + \epsilon)n$$

From Lemma 3.2.1 we have:

$$OPT(I) = 15n - (\frac{7}{8} + \epsilon)n$$

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

196 Therefore, by using assumed to exist $(1 + \epsilon)$ approximation for segment set cover, it's
 197 possible to distinguish S from being satisfiable and at most $(\frac{7}{8} + \epsilon)n$ satisfiable, since there
 198 exists result threshold distinguishing approximation result in segment set cover for these two
 199 cases. This is a contradiction, hence the approximation scheme cannot exist.

3.2.2. Reduction construction

We will show reduction from MAX-(3,3)-SAT problem to geometric set cover with segments parallel to axis. Moreover the instance of geometric set cover will be robust to 1/2-extensions (have the same optimal solution after 1/2-extension).

The construction will be composed of 2 types of gadgets: **variable gadgets** and **clause gadgets**. Clause gadgets would be constructed using two **or gadgets** connected together.

Variable gadget is responsible for choosing a value of variable in CNF formula. It allows two minimal solution and every minimal solution must use exactly one of the a and b segments, so you can assign variable a binary value.

Clause gadget is responsible for calculating if choice of the variable values meets the clauses in formula. It has minimal solution of w if at least one variable in the clause has a correct value. Otherwise it has minimal solution $w + 1$. This way by the minimal solution for the whole problem, we can tell how many clauses were satisfiable.

The clause gadgets consist of smaller or gadgets that have similar property for 2 variables (input segments). There exists an output segment and minimal solution can use the output segments only when at least one of the input segments was chosen for a solution.

We also don't want the clause gadgets to be crammed inbetween the very long variable segments. That's why we have a simple gadget to *pass* the value of the segment, ie. segments $(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1})$

We define:

$$\mathcal{C} := \bigcup_{1 \leq i \leq n} C_variable_i \cup C_clause_i$$

$$\mathcal{P} := \bigcup_{1 \leq i \leq n} P_variable_i \cup P_clause_i$$

We will prove some properties of different gadgets. Every segment for gadget will only cover points in this gadget (won't interact with any different gadget), so we can prove lemmas *locally*.

TODO: y axis is increasing values downward on figures (not upwards like in normal).

3.2.2.1. Variable gadget

Points. Define points:

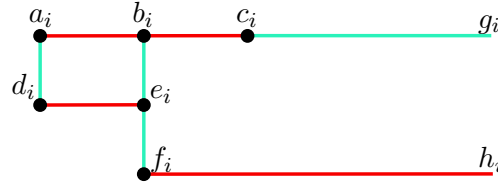


Figure 3.1: **Choose variable value gadget.** We denote set of points marked with black circle as $C_variable_i$ and need to be covered (are part of set \mathcal{C}). We denote set of red segments as x_i^{false} and set of blue segments as x_i^{true} .

TODO: inline $L = 12n$ after finishing these formulas

$$\begin{array}{llll} a_i = (-L, 4i) & b_i = (-\frac{2}{3}L, 4i) & c_i = (-\frac{1}{3}L, 4i) & d_i = (-L, 4i + 1) \\ e_i = (-\frac{2}{3}L, 4i + 1) & f_i = (-\frac{1}{3}L, 4i + 2) & g_i = (L, 4i) & h_i = (L, 4i + 2) \end{array}$$

Let's define

$$C_variable_i = \{a_i, b_i, c_i, d_i, e_i, f_i\}$$

227 **Segments.** Let's define

$$x_i^{true} = \{(a_i, d_i), (b_i, f_i), (c_i, g_i)\}$$

$$x_i^{false} = \{(a_i, c_i), (d_i, e_i), (f_i, h_i)\}$$

$$P_variable_i = x_i^{true} \cup x_i^{false}$$

228 **Lemma 3.2.2** For any $1 \leq i \leq n$, points $C_variable_i$ can be covered using 3 segments from
229 $P_variable_i$.

230 **Proof.** We can use either set x_i^{true} or x_i^{false} .

231 **Lemma 3.2.3** For any $1 \leq i \leq n$, points $C_variable_i$ can not be covered with less than 3
232 segments from $P_variable_i$.

233 **Proof.** There is independent set $\{d_i, f_i, c_i\}$ of size 3, therefore it can not be covered with
234 less than 3 sets (segments).

235 **Lemma 3.2.4** If both segments (c_i, g_i) and (f_i, h_i) are chosen, then the covering the remain-
236 ing points from $C_variable_i$ requires at least 2 different segments from $P_variable_i$.

237 **Proof.** There is an independent set $\{a_i, e_i\}$ of size 2 in $C_variable_i - \{c, f, g, h\}$, therefore
238 it can not be covered with less than 2 sets (segments).

239 3.2.2.2. Or gadget

240 **Points.**

$$\begin{array}{llll} l_0 = (0, 0) & m_0 = (0, 1) & n_0 = (0, 2) & o_0 = (0, 3) \\ 241 \quad p_0 = (0, 4) & q_0 = (1, 1) & r_0 = (1, 3) & s_0 = (2, 1) \\ t_0 = (2, 2) & u_0 = (2, 3) & v_0 = (3, 2) & \end{array}$$

$$vec_{i,j} = (10i + 3 + 3j, 4n + 2j)$$

242 Define $\{l_{i,j}, m_{i,j} \dots v_{i,j}\}$ as $\{l_0, m_0 \dots v_0\}$ shifted by $vec_{i,j}$

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

$$C_or_gadget_{i,j} = \{l_{i,j}, m_{i,j}, n_{i,j}, o_{i,j}, p_{i,j}, q_{i,j}, r_{i,j}, s_{i,j}, t_{i,j}, u_{i,j}\}$$



Figure 3.2: **Or gadget.** We denote these point as $or_gadget_{i,j}$. We denote set of red segments as $or_{i,j}^{false}$, set of blue segments as $or_{i,j}^{true}$, green and yellow segments as $or_move_variable_{i,j}$.

244 **Segments.** We define names subsets of segments, to refer to them in lemmas.

$$or_{i,j}^{false} = \{(q_{i,j}, r_{i,j}), (s_{i,j}, u_{i,j})\}$$

$$or_{i,j}^{true} = \{(m_{i,j}, s_{i,j}), (o_{i,j}, u_{i,j}), (t_{i,j}, v_{i,j})\}$$

$$or_move_variable_{i,j} = \{(l_{i,j}, n_{i,j}), (n_{i,j}, p_{i,j})\}$$

245 Segments in or gadget:

$$P_or_gadget_{i,j} = or_{i,j}^{false} \cup or_{i,j}^{true} \cup or_move_variable_{i,j}$$

246 **Lemma 3.2.5** For any $1 \leq i \leq n, j \in \{0, 1\}$ and $x \in \{l_{i,j}, p_{i,j}\}$ we can cover points in
 247 $C_or_gadget_{i,j} - \{x\} \cup \{v_{i,j}\}$ with 4 segments.

248 **Proof.** We can do that using one segment from $or_move_variable_{i,j}$ (chosen depending on
 249 the value of x) and all segments from $or_{i,j}^{true}$.

250 **Lemma 3.2.6** For any $1 \leq i \leq n, j \in \{0, 1\}$, we can cover points in $C_or_gadget_{i,j}$ with 4
 251 segments from $P_or_gadget_{i,j}$.

252 **Proof.** We can do that using $or_move_variable_{i,j}$ and $or_{i,j}^{false}$.

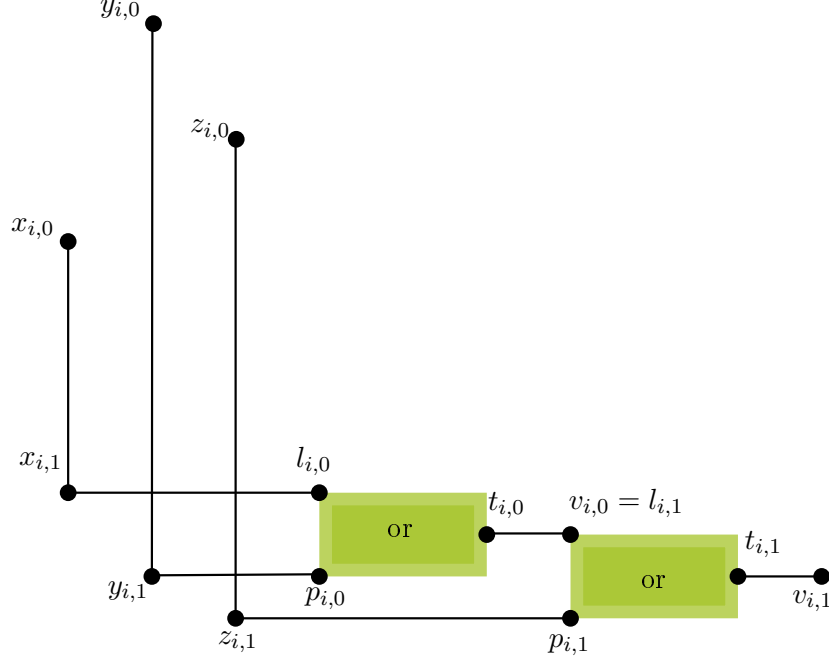


Figure 3.3: **Clause gadget.** We denote set of these points as C_clause_i . Every green rectangle is an or gadget. y -coordinates of $x_{i,0}$, $y_{i,0}$ and $z_{i,0}$ depend on the values of variables in the i -th clause.

253 3.2.2.3. Clause gadget

254 **Points.** TODO: Rephrase it

255 Assuming clause $C_i = x_i \vee y_i \vee z_i$, function $idx(w)$ is returning index of the variable w ,
 256 function $neg(w)$ is returning whether variable w is negated in a clause.

$$\begin{aligned}
 x_{i,0} &= (10i + 1, 4 \cdot idx(x_i) + 2 \cdot neg(x_i)) & x_{i,1} &= (10i + 1, 4n) \\
 y_{i,0} &= (10i + 2, 4 \cdot idx(y_i) + 2 \cdot neg(y_i)) & y_{i,1} &= (10i + 2, 4n + 4) \\
 z_{i,0} &= (10i + 3, 4 \cdot idx(z_i) + 2 \cdot neg(z_i)) & z_{i,1} &= (10i + 3, 4n + 6)
 \end{aligned}$$

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

$$C_clause_i = move_variable_i \cup C_or_gadget_{i,0} \cup C_or_gadget_{i,1} \cup \{v_{i,1}\}$$

Segments.

$$\begin{aligned}
 P_clause_i &= \{(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1}), (x_{i,1}, l_{i,0}), (y_{i,1}, p_{i,0}), (z_{i,1}, p_{i,1}), \} \cup \\
 &\cup P_or_gadget_{i,0} \cup P_or_gadget_{i,1}
 \end{aligned}$$

258 **Lemma 3.2.7** For any $1 \leq i \leq n$ and $a \in \{x_{i,0}, y_{i,0}, z_{i,0}\}$, points $C_clause_i - \{a\}$ can be
 259 covered using 11 segments from P_clause_i .

Proof. For $a = x_{i,0}$ (analogous proof for $y_{i,0}$): First we use Lemma 3.2.5 twice with excluded $x = l_{i,0}$ and $x = l_{i,1} = v_{i,0}$, resulting with 8 segments $or_{i,0}^{true} \cup or_{i,1}^{true}$ 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 $a = z_{0,i}$: Using Lemma 3.2.6 and Lemma 3.2.5 with $x = p_{i,1}$, resulting with 8 segments $or_{i,0}^{false} \cup or_{i,1}^{true}$ 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: $\{(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,1}, p_{i,1})\}$.

Lemma 3.2.8 *Points C_clause_i can be covered with 12 segments from P_clause_i .*

Proof. Using Lemma 3.2.6 twice we can cover $or_gadget_{i,0}$ and $or_gadget_{i,1}$ with 8 segments.

To cover the remaining points we additionally use: $\{(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1}), (t_{i,1}, v_{i,1})\}$

Lemma 3.2.9 *For any $1 \leq i \leq n$, points $C_clause_i - \{x_{i,0}, y_{i,0}, z_{i,0}\}$ can not be covered using less than 11 segments from P_clause_i .*

All points C_clause_i can not be covered with less than 12 segments from P_clause_i .

Proof of no cover with less than 12 segments. There is independent set of 12 points in $C_clause_i \supseteq \{x_{i,0}, y_{i,0}, z_{i,0}, l_{i,0}, p_{i,0}, q_{i,0}, u_{i,0}, v_{i,0} = l_{i,1}, p_{i,1}, q_{i,1}, u_{i,1}, v_{i,1}\}$.

Proof of no cover with less than 11 segments. We can choose disjoint sets X, Y, Z such that $X \cup Y \cup Z \subseteq C_clause_i - \{x_{i,0}, y_{i,0}, z_{i,0}\}$ and there are no segments covering points from different sets. And we will prove lower bounds for each of these sets.

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

Set X is an independent set, so it must be covered with 3 segments.

$$Y = or_gadget_{i,0} - \{l_{i,0}, p_{i,0}\}$$

$$Z = or_gadget_{i,1} - \{l_{i,1}, p_{i,1}\}$$

For both Y and Z we can check all of the subsets of 3 segments with brutforce that none of them cover, so they have to be covered with 4 segments.

TODO: Funny fact, neither Y nor Z doesn't have independent set of size 4.

Therefore C_clause_i must be covered with at least $3 + 4 + 4 = 11$ segments.

3.2.2.4. Summary

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

Lemma 3.2.10 Robustness to 1/2-extensions. *For every segment $s \in \mathcal{P}$, s and $s^{+1/2}$ cover the same points from \mathcal{C} .*

3.2.3. Proofs of construction Lemma 3.2.1

Lemma 3.2.11 *Given an instance of MAX-(3,3)-SAT of size n with optimal solution k . For instance of geometric cover, constructed according to Lemma 3.2.1, there exists a solution of weight $15n - k$.*

Proof. Let's name the assignments of the variables in MAX-(3,3)-SAT instance, that achieve the optimal solution, $y_1, y_2 \dots y_n$. Let's cover every variable gadget with solution described in Lemma 3.2.2, in the i -th gadget choosing the set of segments responsible for the value of y_i (true – x_i^{true} or false – x_i^{false}).

Cover every satisfied clause gadget with solution described in Lemma 3.2.7 and unsatisfied clause gadget with solution from Lemma 3.2.8.

This solution uses $3n + (11m + (m - k)) = 15n - k$ segments.

Lemma 3.2.12 *Given an instance of MAX-(3,3)-SAT of size n , and solution of size w to the instance of geometric cover, constructed according to Lemma 3.2.1, there exists a solution to MAX-(3,3)-SAT of size at least $15n - w$.*

Proof. Among $x_i^{true} \cup x_i^{false}$, we need to use at least 3 segments (Lemma 3.2.3). If we have chosen both segments (c_i, g_i) and (f_i, h_i) , then we have used at least 4 segments (Lemma 3.2.4).

If we chose at most one of the segments (c_i, g_i) and (f_i, h_i) , choose the corresponding variable value to the solution. If we chose both segments, choose the value that appears in most (at least 2) clauses. If we have chosen none of the segments, choose any value.

To cover $\bigcup_{1 \leq i \leq n} C_variable_i$ we have used at least $3n + a$ segments, where a is the number of i such that we have chosen both values (c_i, g_i) and (f_i, h_i) .

Among the segments responsible for the clause $C_i = x \vee y \vee z$ we need to use at least 11 segments (Lemma 3.2.9) and if we can cover it with 11 segments, then we have earlier chosen segment responsible for the value of variable x, y or z that satisfies C_i .

So we have at least 11 segments for satisfied clauses and at least 12 segments for unsatisfied clauses, so we cover it with at least $11n + b$ segments, where b is number of clauses where none of the variables x, y, z were chosen. If the segment responsible for value of x was taken, but this variable is set to have different value, then we have chosen segments for both x and $\neg x$ for this variable, so "we cheated" and this maybe clause is not met, but we assigned the value for this x_i that meets the most clauses, so for each of such "cheated" variables, at most one of the clauses isn't met.

So there are at most $a + b$ unsatisfied clauses in this instance, so we have shown the assignment with at least $n - (a + b)$ satisfied clauses.

$$w \geq 3n + a + 11n + b = 14n + a + b$$

$$15n - w \leq 15n - 14n - a - b = n - (a + b)$$

3.2.3.1. Proof of Lemma 3.2.1

Given an instance of MAX-(3,3)-SAT of size n with optimal result k . Let's construct an instance of geometric cover, constructed in aforementioned manner.

Given the Lemma 3.2.11, we know the optimal solution for the constructed geometric cover is at most $15n - k$ and since the k is optimal solution for MAX-(3,3)-SAT, then according to Lemma 3.2.12 there doesn't exist a solution with cost less than $15n - k$.

3.3. Weighted segments

3.3.1. FPT for weighted segments with δ -extensions

Theorem 3.3.1 (FPT for weighted segment cover with δ -extensions). *There exists an algorithm that given a family \mathcal{P} of n weighted segments (in any direction), a set of m*

331 points \mathcal{C} and a parameter k , runs in time $f(k) \cdot (nm)^c$ for some computable function f and
 332 constant c , and outputs a subfamily $\mathcal{R} \subseteq \mathcal{P}$ such that $|\mathcal{R}| \leq k$ and $\mathcal{R}^{+\delta}$ covers all points in \mathcal{C} .

333 To solve this problem we will introduce kernel for slightly different problem: Weighted
 334 segment cover of points and segments. In shortcut: WSCPS.

335 **Lemma 3.3.1 (Algorithm for kernel of WSCPS).** *There exists an algorithm that given*
 336 *a family \mathcal{P} of n weighted segments (in any direction), a set of m_1 points \mathcal{C}_1 and m_2 segments*
 337 *\mathcal{C}_2 and a parameter k , runs in time $f(k) \cdot g(m_1, m_2) \cdot n^c$ for some computable functions f, g*
 338 *and constant c , and outputs a subfamily $\text{sol} \subseteq \mathcal{P}$ such that $|\text{sol}| \leq k$ and sol covers all points in*
 339 *\mathcal{C}_1 and all segments in \mathcal{C}_2 .*

340 **Proof** Only sketch for now.

341 We can compute dynamic programming $dp(A, B, z)$ – the best cost to cover at least whole
 342 segment A, B using at most z segments. A, B are all interesting points – ends of any segment
 343 given on the input or points given on the input. We can compute it in polynomial time.

344 Then we can create a new double weighted set (original weight, number of used segments
 345 from \mathcal{P}) – \mathcal{P}_2 that has only segments which never cover partially any segment from \mathcal{C}_2 (covers
 346 the whole segment or doesn't cover at all). In such \mathcal{P}_2 we can find solution \mathcal{R} where any
 347 2 segments have empty intersection (don't cover each other and don't meet at the ends).
 348 Because if we had such solution, we can merge these two segments and such segment there's
 349 also in \mathcal{P}_2 .

350 In that case we can find kernel of \mathcal{P}_2 of size $k \cdot (m_1 + 2m_2)^2$, because we only need to take
 351 the best weight covering some subset of $\mathcal{C}_1 \cup \mathcal{C}_2$.

352 **Lemma 3.3.2 Kernel in WSCPS.** *TODO: formulate it properly*

353 *For segment cover, there is a kernel of size $f(k)$ in WSCPS.*

354 **Claim 3.3.1** *If there are more than k lines with at least $k+1$ points on them, then they can't*
 355 *be covered with k segments.*

356 **Claim 3.3.2** *If there is more than k^2 points that don't lie on any line with more than k points*
 357 *on it, then they can't be covered with k segments.*

358 **Claim 3.3.3** *For every long line L (with more than k points on them) we can choose $f(k)$*
 359 *points on them, that if we cover all of these points with at most k segments, then the rest of*
 360 *the points with δ -extensions will be covered by segments in the direction of line L .*

361 **Proof of Lemma 3.3.2.** After applying the previous lemmas, we have at most $k^2 + k \cdot f(k)$
 362 points that can be covered in any direction and for the rest of the points we can draw at most
 363 $k \cdot f(k)$ segments along their respective long lines that have to be covered by segments after
 364 δ -extensions.

365 Then we extend every available segment by δ -extension and we achieve the kernel in
 366 WSCPS for this instance of problem.

367 **Lemma 3.3.3** *If all the points are covered with k segments and the biggest $2(1 + 1/\delta)^{k+1}$*
 368 *spaces between points are filled, the whole segment is filled after δ -extensions of these segments.*

369 **Proof.** Let's name the $2(1+1/\delta)^{k+1}$ -st biggest space between points as y . We have guarantee
370 that all segments of length $x > y$ are covered without δ -extensions.

371 Let's take one space between points that is not covered before δ -extension and we will
372 prove it will be covered after δ -extensions. Let's assume it isn't.

373 This space has length x . Since it's uncovered, $x \leq y$.

374 Let's take side where the sum of lengths of segments covering the points is greater (left or
375 right). Without loss of generality, let us assume it's right.

376 There are at most k segments to the right of this space between points. Name their lengths
377 $l_1, l_2 \dots l_k$. If the point is covered in the other direction, the segment is degenerated to the
378 point and $l_i = 0$. Name the space between endpoints of l_i and $l_{i+1} - x_i$. Of course, x_i is
379 uncovered space between two points, therefore $x_i \leq y$.

380 TUTAJ BEDZIE PEWNIE RYSUNEK Z TYMI SUPER RZECZAMI DO PRZERW

381 Let's write equations meaning that i -th segment doesn't cover space x after δ -expansion.

$$l_1\delta < x \leq y \Rightarrow l_1 < y/\delta$$

$$l_2\delta < x + l_1 + x_1 < 2y + y/\delta \Rightarrow l_2 < 2y/\delta + y/\delta^2$$

$$l_3\delta < x + l_1 + x_1 + l_2 + x_2 < 3y + 3y/\delta + y/\delta^2 \Rightarrow l_3 < 3y/\delta + 3y/\delta^2 + y/\delta^3$$

382 From this we can "guess" induction $l_i < y((1 + 1/\delta)^i - 1)$

383 Trivially for $l_1 < y/\delta$.

Assume that for all $j < i$:

$$l_j < y((1 + 1/\delta)^j - 1)$$

384 .

$$\begin{aligned} 385 \quad l_i\delta &< x + \sum_{j=1}^{i-1} (l_j + x_j) < iy \sum_{j=1}^{i-1} l_j < iy + \sum_{j=1}^{i-1} j = 1^{i-1}y((1 + 1/\delta)^j - 1) = iy - (i - \\ 386 \quad 1)y + \sum_{j=1}^{i-1} j &= 1^{i-1}y(1 + 1/\delta)^j = y(1 + \sum_{j=1}^{i-1} (1 + 1/\delta)^j) = y(2 + \sum_{j=1}^{i-1} (1 + 1/\delta)^j - 1) = \\ 387 \quad y(\sum_{j=0}^{i-1} (1 + 1/\delta)^j - 1) &= y((1 + 1/\delta)^i / (1 - (1 + 1/\delta)) - 1) = y((1 + 1/\delta)^i \delta - 1) < y((1 + 1/\delta)^i \delta - \delta) \end{aligned}$$

Of course we also know that (since we have chosen the side with greater sum of the width of segments):

$$\sum_{i=1}^k l_i \geq 1/2 \cdot y \cdot 2(1 + 1/\delta)^{k+1} = y \cdot (1 + 1/\delta)^{k+1}$$

$$\begin{aligned} 388 \quad \text{But } \sum_{i=1}^k l_i &< \sum_{i=1}^k y((1 + 1/\delta)^i - 1) = y((1 + 1/\delta)^{k+1} / (1 - (1 + 1/\delta)) - k) = y((1 + \\ 389 \quad 1/\delta)^{k+1} \delta - k) &< y(1 + 1/\delta)^{k+1} \end{aligned}$$

390 Therefore the space must have been covered after δ -expansions.

391 3.3.2. W[1]-completeness for weighted segments in 3 directions

392 **Theorem 3.3.2** *W[1]-completeness for weighted segments in 3 directions.* Consider
393 the problem of covering a set \mathcal{C} of points by selecting k axis-parallel or right-diagonal weighted
394 segments with weights from a set \mathcal{P} with minimal weight. Assuming ETH, there is no algorithm
395 for this problem with running time $f(k) \cdot (|\mathcal{C}| + |\mathcal{P}|)^{o(\sqrt{k})}$ for any computable function f .

396 We will show reduction from grid tiling problem.

397 Let's have an instance of grid tiling problem – size of the grid k , number of elements
398 available n and k^2 sets of available pairs in every tile $S_{i,j} \subseteq \{1, n\} \times \{1, n\}$.

399 **Construction.** We construct a set \mathcal{P} of segments and a set \mathcal{C} of points.

400 First let's choose any ordering of n^2 elements $\{1, n\} \times \{1, n\}$ and name this sequence

401 $a_1 \dots a_{n^2}$.

$$match_v(i, j) \iff a_i = \{x_i, y_i\} \wedge a_j = \{x_j, y_j\} \wedge x_i = x_j$$

$$match_h(i, j) \iff a_i = \{x_i, y_i\} \wedge a_j = \{x_j, y_j\} \wedge y_i = y_j$$

Points. Define points:

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

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

Let's define sets H and V as:

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

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

402 Let's define $\epsilon = 0.1$. For a point $\{x, y\} = p$ we define points $p^L = \{x - \epsilon, y\}$, $p^R = \{x + \epsilon, y\}$,

403 $p^U = \{x, y - \epsilon\}$, and $p^D = \{x, y + \epsilon\}$.

Then we define:

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

404 **Segments.** Define horizontal segments.

$$hor_{i,j,t_1,t_2} = (h_{i,j,t_1}^R, h_{i,j+1,t_2}^L)$$

$$ver_{i,j,t_1,t_2} = (v_{i,j,t_1}^D, v_{i,j+1,t_2}^U)$$

$$horbeg_{i,t} = (h_{i,1,1}^L, h_{i,1,t}^L)$$

$$horend_{i,t} = (h_{i,n,t}^R, h_{i,n,n^2}^R)$$

$$verbeg_{i,t} = (v_{i,1,1}^U, v_{i,1,t}^U)$$

$$verend_{i,t} = (v_{i,n,t}^D, v_{i,n,n^2}^D)$$

$$\begin{aligned} HOR &= \{hor_{i,j,t_1,t_2} : 1 \leq i \leq k, 1 \leq j < k, 1 \leq t_1, t_2 \leq n^2, match_h(t_1, t_2)\} \\ &\cup \{horbeg_{i,t} : 1 \leq i \leq k, 1 \leq t \leq n^2\} \\ &\cup \{horend_{i,t} : 1 \leq i \leq k, 1 \leq t \leq n^2\} \end{aligned}$$

$$\begin{aligned} VER &= \{ver_{i,j,t_1,t_2} : 1 \leq i \leq k, 1 \leq j < k, 1 \leq t_1, t_2 \leq n^2, match_v(t_1, t_2)\} \\ &\cup \{verbeg_{i,t} : 1 \leq i \leq k, 1 \leq t \leq n^2\} \\ &\cup \{verend_{i,t} : 1 \leq i \leq k, 1 \leq t \leq n^2\} \end{aligned}$$

$$DIAG := \{(h_{i,j,t}, v_{j,i,t}) : 1 \leq i, j \leq k, 1 \leq t \leq n^2, a_t \in S_{i,j}\}$$

405 TODO: explain that these segments are in fact diagonal

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

406 **Lemma 3.3.4** *If there exists solution for grid tiling, then there exists solution for our construction using $2(k+1)k + k^2$ segments with weight exactly $2k \cdot (k(n^2 + 1) - 2 - 2\epsilon(k-1))$.*

Claim 3.3.4 *If there exists a solution to the grid tiling $c_1 \dots c_k$ and $r_1 \dots r_k$, then there exists a solution covering all points*

$$\{h_{i,j,t} : 1 \leq i, j \leq k, t = (c_i, r_j)\} \cup \{v_{i,j,t} : 1 \leq i, j \leq k, t = (c_j, r_i)\}$$

408 *with segments in DIAG and the rest in VER or HOR and has weight $2k \cdot (k(n^2 + 1) - 2 - 2\epsilon(k-1))$.*

410 **Proof.** TODO: jakiś prosty z definicji

411 **Lemma 3.3.5** *If there exists solution for our construction using $2(k+1)k + k^2$ segments with weight exactly $2k \cdot (k(n^2 + 1) - 2 - 2\epsilon(k-1))$, then there exists a solution for grid tiling*

413 **Proof.** This follows from Lemma 3.3.6, because we just take which points are covered with
414 *DIAG.*

415 **Claim 3.3.5** *Points p^L, p^R, p^U, p^D cannot be covered with DIAG.*

416 **Claim 3.3.6** *Points in $H \cup \{p^L : p \in H\} \cup \{p^R : p \in H\}$ cannot be covered with VER.*
417 *Points in $V \cup \{p^U : p \in V\} \cup \{p^D : p \in V\}$ cannot be covered with HOR.*

418 **Claim 3.3.7** *For given i, j if none of the points $h_{i,j,t}$ ($v_{i,j,t}$) for $1 \leq t \leq n^2$ are covered with
419 *DIAG, then some spaces between neighbouring points were covered twice.**

420 **Claim 3.3.8** *For given i, j two points h_{i,j,t_1}, h_{i,j,t_2} (v_{i,j,t_1}, v_{i,j,t_2}) for $1 \leq t_1 < t_2 \leq n^2$ are
421 *covered with DIAG, then one of them had to be also covered with a segment from HOR*
422 *(VER).**

423 **Proof.** Point v_{i,j,t_2}^L had to be covered with VER from Claims 3.3.5 and 3.3.6. And every
424 segment in VER covering v_{i,j,t_2}^L , covers also v_{i,j,t_1}^L .

425 **Lemma 3.3.6** *If there exists solution for our construction with weight at most (exactly) $2k \cdot$
426 $(k(n^2 + 1) - 2 - 2\epsilon(k-1))$, then for every i, j there must be exactly one t such that $h_{i,j,t}$ ($v_{i,j,t}$)
427 *is covered with DIAG and moreover if h_{i,j,t_1} and $h_{i,j+1,t_2}$ are uncovered, then $\text{math}_h(t_1, t_2)$.*
428 *Analogically for v .**

429 **Proof.** Only k^2 points can be covered only in DIAG, the rest has to be covered with
430 *VER \cup HOR.* Therefore every result must be at least *ALL_LINES* - $2k^2\epsilon$, because only
431 $2k^2$ spaces of length ϵ can be uncovered in this axis.

432 Of course if h_{i,j,t_1} and $h_{i,j+1,t_2}$ are uncovered, then there must exist a segment in HOR
433 between h_{i,j,t_1}^R and $h_{i,j+1,t_2}^L$, so $\text{math}_h(t_1, t_2)$ must be true.

434 3.3.3. What is missing

435 We don't know FPT for axis-pararell segments without δ -extensions.

Chapter 4

Geometric Set Cover with lines

4.1. Lines parallel to one of the axis

When \mathcal{R} consists only of lines parallel to one of the axis, the problem can be solved in polynomial time.

We create bipartial graph G with node for every line on the input split into sets: H – horizontal lines and V – vertical lines. If any two lines cover the same point from \mathcal{C} , then we add edge between them.

Of course there will be no edges between nodes inside H , because all of them are parallel and if they share one point, they are the same lines. Similar argument for V . So the graph is bipartial.

Now Geometric Set Cover can be solved with Vertex Cover on graph G . Since Vertex Cover (even in weighted setting) on bipartial graphs can be solved in polynomial time.

Short note for myself just to remember how to this in polynomial time:

Non-weighted setting - Konig theorem + max matching

Weighted setting - Min cut in graph of $\neg A$ or $\neg B$ (edges directed from V to H)

4.2. FPT for arbitrary lines

You can find this in Platypus book. We will show FPT kernel of size at most k^2 .

(Maybe we need to reduce lines with one point/points with one line).

For every line if there is more than k points on it, you have to take it. At the end, if there is more than k^2 points, return NO. Otherwise there is no more than k^4 lines.

In weighted settings among the same lines with different weights you leave the cheapest one and use the same algorithm.

4.3. APX-completeness for arbitrary lines

We will show a reduction from Vertex Cover problem. Let's take an instance of the Vertex Cover problem for graph G . We will create a set of $|V(G)|$ pairwise non-parallel lines, such that no three of them share a common point.

Then for every edge in $(v, w) \in E(G)$ we put a point on crossing of lines for vertices v and w . They are not parallel, so there exists exactly one such point and any other line doesn't cover this point (any three of them don't cross in the same point).

Solution of Geometric Set Cover for this instance would yield a sound solution of Vertex Cover for graph G . For every point (edge) we need to choose at least one of lines (vertices) v or w to cover this point.

Vertex Cover for arbitrary graph is APX-complete, so this problem is also APX-complete.

4.4. 2-approximation for arbitrary lines

Vertex Cover has an easy 2-approximation algorithm, but here very many lines can cross through the same point, so we can do d -approximation, where d is the biggest number of lines crossing through the same point. So for set where any 3 lines don't cross in the same point it yields 2-approximation.

The problematic cases are where through all points cross at least k points and all lines have at least k points on them. It can be created by casting k -grid in k -D space on 2D space.

Greedy algorithm yields $\log |\mathcal{R}|$ -approximation, but I have example for this for bipartial graph and reduction with taking all lines crossing through some point (if there are no more than k) would solve this case. So maybe it works.

Unfortunately I haven't done this :(

I can link some papers telling it's hard to do.

4.5. Connection with general set cover

Problem with finite set of lines with more dimensions is equivalent to problem in 2D, because we can project lines on the plane which is not perpendicular to any plane created by pairs of (point from \mathcal{C} , line from \mathcal{P}).

Of course every two lines have at most one common point, so is every family of sets that have at most one point in common equivalent to some geometric set cover with lines?

No, because of Desargues's theorem. Have to write down exactly what configuration is banned.

490 Chapter 5

491 Geometric Set Cover with polygons

492 5.1. State of the art

493 Covering points with weighted discs admits PTAS [Li and Jin, 2015] and with fat polygons
494 with δ -extensions with unit weights admits EPTAS [Har-Peled and Lee, 2009].

495 Although with thin objects, even if we allow δ -expansion, the Set Cover with rectangles is
496 APX-complete (for $\delta = 1/2$), it follows from APX-completeness for segments with δ -expansion
497 in Section 3.2.

498 Covering points with squares is W[1]-hard [Marx, 2005]. It can be proven that assuming
499 *SETH*, there is no $f(k) \cdot (|\mathcal{C}| + |\mathcal{P}|)^{k-\epsilon}$ time algorithm for any computable function f and
500 $\epsilon > 0$ that decides if there are k polygons in \mathcal{P} that together cover \mathcal{C} , *Theorem 1.9* in [Marx
501 and Pilipczuk, 2015].

502 Chapter 6

503 Conclusions

504 Bibliography

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