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Approximation and Parametrized Algorithms for Segment Set Cover

Master's thesis
in COMPUTER SCIENCE

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Supervisor's statement

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

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

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Abstract

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

Keywords

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

Thesis domain (Socrates-Erasmus subject area codes)

11.3 Informatyka

Subject classification

D. Software
D.127. Blabalgorithms
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Tytuł pracy w języku polskim

Algorytmy parametryzowania i trudność aproksymacji problemu pokrywania zbiorów odcinkami na płaszczyźnie

Contents

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 were 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 suffciently small $\epsilon > 0$, the problem does not admit $1 + \epsilon$-approximation scheme) [refrencje].

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 segments 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 unweighed 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.

Chapter 2

Definitions

2.1. Geometric Set Cover

In the geometric set cover problem we are are given $\mathcal{P}$ – set of objects, $\mathcal{C}$ – set of points. The task is to choose $\mathcal{R} \subseteq \mathcal{P}$ such that every point in $\mathcal{C}$ is inside some element from $\mathcal{R}$ and $|\mathcal{R}|$ is minimal.

In the parametrized setting for a given k, we only look for a solution $\mathcal{R}$ such that $|\mathcal{R}| \leq k$.

In the weighted setting, there is some given weight function $f : \mathcal{P} \to \mathbb{R}^+$, and we would like to minimize $\sum_{R\in\mathcal{R}} f(R)$.

2.2. Approximation

Let us recall some of the definitions related to approximation problems that will be used in the following sections.

Definition 2.2.1. *A **polynomial-time approximation scheme (PTAS)** for a minimization problem Π is a family of algorithms $\mathcal{A}_\epsilon$ for every $\epsilon > 0$, such that $\mathcal{A}_\epsilon$ takes an instance I of Π and in polynomial time finds a solution that is within a factor $(1+\epsilon)$ of being optimal. That means the reported solution has weight at most $(1+\epsilon)opt(I)$, where $opt(I)$ is the weight of an optimal solution for I.*

Definition 2.2.2. *Problem is **APX-hard** if assuming $P \neq NP$, there exists such $\epsilon > 0$ such that there is no polynomial time $(1+\epsilon)$-approximation algorithm.*

2.3. δ-extensions

TODO PLACEHOLDER for introductory text

δ-extensions is one of the modifications to a problem, that makes geometric set cover problem easier, it has been already used in literature (place some refrence here).

Definition 2.3.1. ***δ-extensions for center-symmetric objects*** *For any $\delta > 0$ and center-symmetric gemetric object L with centre of symmetry $S = (x_s, y_s)$, a **δ-extension** of this object, $L^{+\delta}$, is an object without border, but with all vertices extended by δd, i.e. $L^{+\delta} = \{(1+\delta)\cdot(x - x_s, y - y_s) + (x_s, y_s) : (x, y) \in L\}$.*

A relaxed cover problem with δ-extensions is a modified version of a problem where:

- We need to cover all the points in $\mathcal{C}$ with objects from $\{P^{+\delta} : P \in \mathcal{P}\}$ (which always include no less points than the objects before δ-extensions);

- We look for a solution that is no larger than the optimal solution of the original problem. It doesn't need to be an optimal solution in the modified problem.

Definition 2.3.2. ***Geometric set cover problem with δ-extensions*** *We define an optimization cover problem $\mathcal{P}$ with δ-extensions as the problem where for an input instance I, the task is to output a solution $\mathcal{R}$, such that the δ-extended set $\{R^{+\delta} : R \in \mathcal{R}\}$ covers I and is no worse than the optimal solution for the problem without extensions, i.e. $|\mathcal{R}| \leq |\mathcal{R}^{opt}|$.*

Definition 2.3.3. ***Geometric set cover PTAS with δ-extensions*** *We define a PTAS for cover problem $\mathcal{P}$ with δ-extensions as an algorithm that takes as an input instance I, and outputs a solution $\mathcal{R}$, such that the δ-extended set $\{R^{+\delta} : R \in \mathcal{R}\}$ covers I and is within a $(1+\epsilon)$ factor of the optimal solution for this problem without extensions, i.e. $(1+\epsilon)|\mathcal{R}| \leq |\mathcal{R}^{opt}|$.*

Chapter 3

Geometric Set Cover with segments

3.1. FPT for segments

3.1.1. Segments parallel to one of the axis

You can find this in Platypus book.

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

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

3.1.2. Segments in d directions

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

3.1.3. Segments in arbitrary direction

Theorem 3.1.1. ***(FPT for segment cover)***. *There exists an algorithm that given a family $\mathcal{P}$ of n segments (in any direction), a set of m points $\mathcal{C}$ and a parameter k, runs in time $f(k) \cdot (nm)^c$ for some computable function f and constant c, and outputs a subfamily $\mathcal{R} \subseteq \mathcal{P}$ such that $|\mathcal{R}| \leq k$ and $\mathcal{R}$ covers all points in $\mathcal{C}$ or determins that the solution of size at most k doesn't exist.*

This theorem is proved by following lemmas.

Lemma 3.1.1. ***(Reduction)***. *Given a family $\mathcal{P}$ of n segments (in any direction), a set of m points $\mathcal{C}$ for segment cover problem, without a loss of generality we can assume that no two segments cover the same set of points.*

Proof. Trivial.

Lemma 3.1.2. ***(Kernel for segment cover)***. *For a problem of segment cover that given a family $\mathcal{P}$ of n segments (in any direction), a set of m points $\mathcal{C}$ and a parameter k, there exists a family of kernels $K \subset \mathcal{P}$, where any line contains no more than k points and there exists optimal solution, that is subset of K. We can find all such kernels in complexity $O(k^k)$ using branching technique and there are $O(k^k)$ of them.*

Proof. First we use Lemma 3.1.1.

Assume there exists a line l containing points $x_1, \ldots x_t$, 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, ..., 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 (We branch over $i \in \{1 \ldots k+1\}$. 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 $O(k^k)$.

Proof of theorem 3.1.1. Assuming Lemma 3.1.2.

First we use Lemma 3.1.1.

Since any segment covers a set of colinear points, for such a kernel k segments can cover only at most k^2 points. Therefore, for the answer to be positive, the number of points has to be at most k^2. The number of segments is now bounded by k^4, since if we consider two *extreme* points covered by a given segment, then these pairs must be distinct, otherwise two 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 $O(f(k))$. Since there are $O(k^k)$ possible kernels, the final algotihm work in $f(k) \cdot (nm)$.

3.2. APX-completeness for segments parallel to axes

In this section we analyze whether there exists an $(1+\epsilon)$-approximation scheme 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 3.2.1. ***(axis-parallel segment set cover with 1/2-extension is APX-hard).*** *Unweighted geometric set cover with axis-parallel segments in 2D (even with 1/2-extension) is APX-hard. That is, assuming $P \neq NP$, there does not exist a PTAS for this problem.*

Theorem 3.2.1 implies the following.

Corollary 3.2.1. ***(rectangle set cover is APX-hard).*** *Unweighted geometric set cover with rectangles (even with 1/2-extension) is APX-hard.*

We prove Theorem 3.2.1 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.

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 $(1+\epsilon)$-approximation algorithm for J would be able to distinguish whether an instance I of MAX-(3,3)-SAT is fully satisfiable or $(7/8+\epsilon)$-satisfiable. However, according to (Theorem 3.2.2) that problem is NP-hard. That would imply P = NP, contradicting the assumption.

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

Definition 3.2.1. ***MAX-3SAT*** *is a maximization problem. We are given a 3-CNF formula, and need to find an assignment of variables that satisfies the most clauses.*

Definition 3.2.2. ***MAX-(3,3)-SAT*** *is MAX-3SAT with an additional restriction that every variable appears in exactly 3 clauses. Note that thus, the number of clauses is equal to number of variables.*

In the lemmas above we use a property of MAX-(3,3)-SAT proved in [Håstad, 2001] and described in Theorem 3.2.2.

Theorem 3.2.2. ***[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.

The following lemma encapsulates the properties of the reduction described in this section, and it allows us to prove Theorem 3.2.1.

Lemma 3.2.1. *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 with $1/2$-extensions, such that:*

(1) For every solution X of instance I, there exists a solution of S of size at least $15n - |X|$.

(2) For every solution X of instance S, there exists a solution of I of size $15n - |X|$.

(3) Every solution with $1/2$-extensions for I is also a solution to the original instance I.
Therefore, the optimal solution of I is $OPT(I) = 15n - OPT(S)$.

We prove Lemma 3.2.1 in subsequent sections, but meanwhile let us prove Theorem 3.2.1 using Lemma 3.2.1 and Theorem 3.2.2.

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Proof of Theorem 3.2.1 . 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 $(1/2)$-extensions. We construct an algorithm that solves the problem stated in Theorem 3.2.2, 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 3.2.1.

We now use the $(1 + \epsilon)$-approximation algorithm for geometric set cover on I, denote the cost of the result of applying 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 3.2.1 we have:

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

Therefore,

$$approx(I) \leq (1 + \epsilon)OPT(I) = 14n(1 + \epsilon) = 14n + 14\epsilon \cdot n =$$
$$= 14n + (15\epsilon - \epsilon)n < 14n + \left(\frac{1}{8} - \epsilon\right)n = 15n - \left(\frac{7}{8} + \epsilon\right)n$$

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

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

From Lemma 3.2.1 we have:

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

Since a solution to I with extensions is also a solution without extentions, by Lemma 3.2.1 (3.), we have:

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

Therefore, by using the assumed $(1+\epsilon)$-approximation algorithm, it is possible to distinguish the case when S is satisfiable from the case when it is at most $(\frac{7}{8}+\epsilon)n$ satisfiable, since there exists a threshold on the approximation result in segment set cover that distinguishes these two cases. Hence, the assumed approximation algorithm cannot exist, unless P = NP.

3.2.2. Reduction construction

We 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.

3.2.2.1. VARIABLE-gadget

VARIABLE-gadget is responsible for choosing the value of a variable in a CNF formula. It allows two minimal solutions and every minimal solution must use exactly one of the (c_i, g_i) and (f_i, h_i) segments. These two choices correspond to the two Boolean values of the variable.

Points. Define points:

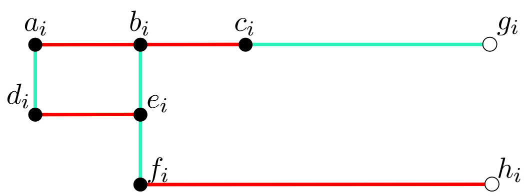

Figure 3.1: **VARIABLE-gadget.** We denote the set of points marked with black circles as C^i_{var}, and they need to be covered (are part of the set $\mathcal{C}$). Note that some of the points are not marked as black dots and exists only to name segments for further reference. We denote the set of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

With $L = 12n$:

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

Let us define:

$$C_{var} = \{a, b, c, d, e, f\}$$

and

$$C^i_{var} = C_{var} + (0, 4i)$$

Segments. Let us define:

$$X^i_{true} = \{(a_i, d_i), (b_i, f_i), (c_i, g_i)\}$$
$$X^i_{false} = \{(a_i, c_i), (d_i, e_i), (f_i, h_i)\}$$

$$P^i_{var} = X^i_{true} \cup X^i_{false}$$

Lemma 3.2.2. *For any $1 \leq i \leq n$, points C^i_{var} can be covered using 3 segments from P^i_{var}.*

Proof. We can use either set X^i_{true} or X^i_{false}. □

Lemma 3.2.3. *For any $1 \leq i \leq n$, points C^i_{var} can not be covered with less than 3 segments from P^i_{var}.*

Proof. No segment of P^i_{var} covers more than one point from $\{d_i, f_i, c_i\}$, therefore C^i_{var} can not be covered with less than 3 segments. □

Lemma 3.2.4. *If both segments (c_i, g_i) and (f_i, h_i) are chosen, then the covering the remaining points from C^i_{var} requires at least 2 different segments from P^i_{var}.*

Proof. No segment of P^i_{var} covers more than one point from $\{a_i, e_i\}$, therefore C^i_{var} - $\{c_i, f_i, g_i, h_i\}$ can not be covered with less than 2 segments. □

3.2.2.2. OR-gadget

OR-gadget has 3 important segments – $x, y, result$. x and y don't count to the weight of solution of OR-gadget (they are part of different gadgets). It has a minimal solution of weight w and $result$ can be chosen only if x or y are also chosen for the solution. If none of them are chosen, then solution choosing $result$ segment has weight at least $w + 1$. Therefore the following formula holds for a solution R assuming that R uses only w from this OR-gadget:

$$(x \in R) \vee (y \in R) \iff result \in R$$

Points.

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

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

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

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

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

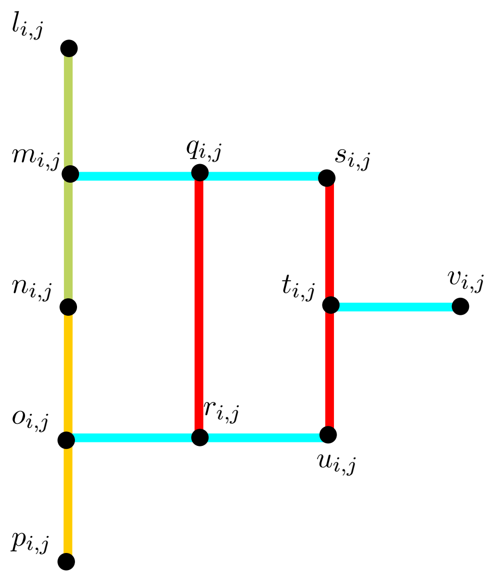

Figure 3.2: **OR-gadget.** We denote these point as $or\_gadget_{i,j}$. We denote set of red segments as $or_{i,j}^{false}$, set of blue segments as $or_{i,j}^{true}$, green and yellow segments as $or\_move\_variable_{i,j}$.

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

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

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

$$or\_move\_variable_{i,j} = \{(l_{i,j}, n_{i,j}), (n_{i,j}, p_{i,j})\}$$

Segments in OR-gadget:

$$P\_or\_gadget_{i,j} = or_{i,j}^{false} \cup or_{i,j}^{true} \cup or\_move\_variable_{i,j}$$

Lemma 3.2.5. *For any $1 \le i \le n, j \in \{0, 1\}$ and $x \in \{l_{i,j}, p_{i,j}\}$ we can cover points in $C\_or\_gadget_{i,j} - \{x\} \cup \{v_{i,j}\}$ with 4 segments.*

Proof. We can do that using one segment from $or\_move\_variable_{i,j}$ (chosen depending on the value of x) and all segments from $or_{i,j}^{true}$.

Lemma 3.2.6. *For any $1 \le i \le n, j \in \{0, 1\}$, we can cover points in $C\_or\_gadget_{i,j}$ with 4 segments from $P\_or\_gadget_{i,j}$.*

Proof. We can do that using $or\_move\_variable_{i,j}$ and $or_{i,j}^{false}$.

3.2.2.3. CLAUSE-gadget

CLAUSE-gadget is responsible for calculating if choice of the variable values meets the clause in formula. It has minimal solution of weight 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 two OR-gadgets. We don't want the CLAUSE-gadgets to be crammed somewhere between the very long variable segments. That's why we have a simple gadget to *pass* the value of the segment, ie. segments $(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1})$. Two segments and one of them is chosen if x was chosen in the solution and the other one if x wasn't.

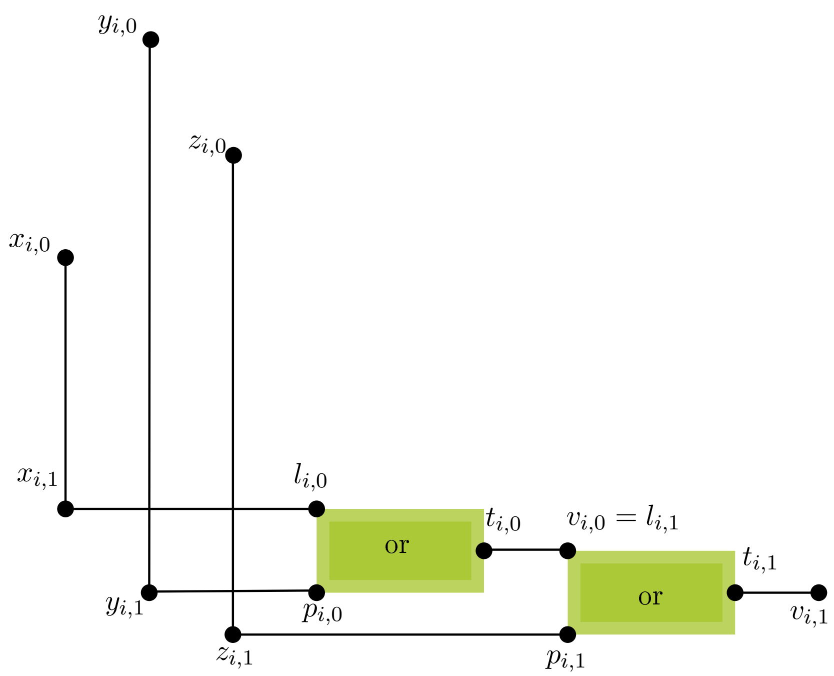

Figure 3.3: **CLAUSE-gadget.** We denote set of these points as C_clause_i. Every green rectangle is an OR-gadget. y-coordinates of $x_{i,0}$, $y_{i,0}$ and $z_{i,0}$ depend on the values of variables in the i-th clause.

Points. TODO: Rephrase it

Assuming clause $C_i = x_i \vee y_i \vee z_i$, function $idx(w)$ is returning index of the variable w, 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.

$$\begin{aligned} P\_clause_i &= \{(x_{i,0}, x_{i,1}), (y_{i,0}, y_{i,1}), (z_{i,0}, z_{i,1}), (x_{i,1}, l_{i,0}), (y_{i,1}, p_{i,0}), (z_{i,1}, p_{i,1}), \} \cup \\ &\cup P\_or\_gadget_{i,0} \cup P\_or\_gadget_{i,1} \end{aligned}$$

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 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 prove lower bounds for each of these sets.

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

Set X is an indendent 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 $\mathcal{C}$.*

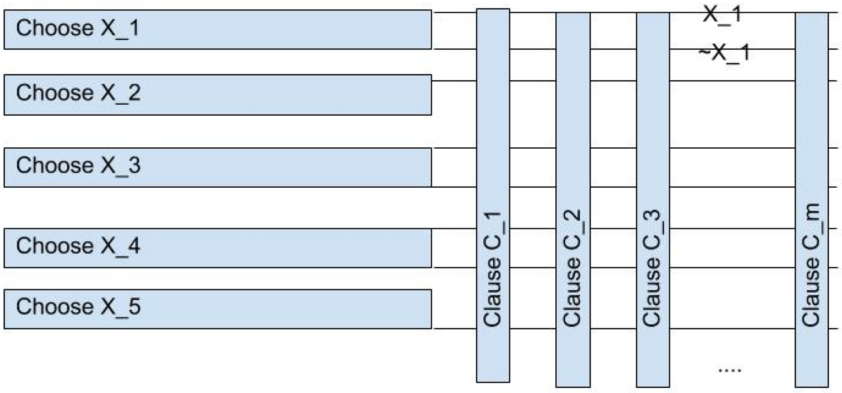

Figure 3.4: **General schema.**
General layout of VARIABLE-gadget and CLAUSE-gadget and how they interact with each other.
TODO: Rename Choose X to VARIABLE-gadget and Clause C to CLAUSE-gadget.

3.2.3. Summary of contruction

We define:

$$\mathcal{C} := \bigcup_{1 \leq i \leq n} C\_variable_i \cup C\_clause_i$$

$$\mathcal{P} := \bigcup_{1 \leq i \leq n} P\_variable_i \cup P\_clause_i$$

The subsequent sections define these sets.

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

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

3.2.4. 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 … 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 $\bigcup_{1 \le i \le n} C\_variable_i$ 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 $a + b$ unsatsfied clauses in this instance, so we have shown the assignment with at least $n - (a + b)$ satisfied clauses.

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

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

3.2.4.1. 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*

points $\mathcal{C}$ and a parameter k, runs in time $f(k) \cdot (nm)^c$ for some computable function f and 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 $\mathcal{C}$.

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

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

Proof Only sketch for now.

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

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

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 the best weight covering some subset of $\mathcal{C}_1 \cup \mathcal{C}_2$.

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

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

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

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

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

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

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

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

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

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

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

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

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

TUTAJ BEDZIE PEWNIE RYSUNEK Z TYMI SUPER RZECZAMI DO PRZERW

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

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

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

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

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

Trivailly for $l_1 < y/\delta$.

Assume that for all $j < i$:

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

.

$l_i\delta < x + \sum_{j=1}^{i-1}(l_j + x_j) < iy\sum_{j=1}^{i-1} l_j < iy + \sum j = 1^{i-1} y((1 + 1/\delta)^j - 1) = iy - (i - 1)y + \sum j = 1^{i-1} y(1 + 1/\delta)^j = y(1 + \sum_{j=1}^{i-1}(1 + 1/\delta)^j) = y(2 + \sum_{j=1}^{i-1}(1 + 1/\delta)^j - 1) = y(\sum_{j=0}^{i-1}(1+1/\delta)^j - 1) = y((1+1/\delta)^i/(1-(1+1/\delta))-1) = y((1+1/\delta)^i\delta - 1) < y((1+1/\delta)^i\delta - \delta)$

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

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

But $\sum_{i=1}^{k} l_i < \sum_{i=1}^{k} y((1 + 1/\delta)^i - 1) = y((1 + 1/\delta)^{k+1}/(1 - (1 + 1/\delta)) - k) = y((1 + 1/\delta)^{k+1}\delta - k) < y(1 + 1/\delta)^{k+1}$

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

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

Theorem 3.3.2. ***W[1]-completeness for weighted segments in 3 directions.*** *Consider the problem of covering a set $\mathcal{C}$ of points by selecting k axis-pararell or right-diagonal weighted segments with weights from a set $\mathcal{P}$ with minimal weight. 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.*

We will show reduction from grid tiling problem.

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

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

First let's choose any ordering of n^2 elements $\{1,n\} \times \{1,n\}$ and name this sequence $a_1 \dots a_{n^2}$.

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

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

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:

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

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

Then we define:

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

Segments. Define horizontal segments.

$$hor_{i,j,t_1,t_2} = (h^R_{i,j,t_1}, h^L_{i,j+1,t_2})$$
$$ver_{i,j,t_1,t_2} = (v^D_{i,j,t_1}, v^U_{i,j+1,t_2})$$

$$horbeg_{i,t} = (h^L_{i,1,1}, h^L_{i,1,t})$$
$$horend_{i,t} = (h^R_{i,n,t}, h^R_{i,n,n^2})$$

$$verbeg_{i,t} = (v^U_{i,1,1}, v^U_{i,1,t})$$
$$verend_{i,t} = (v^D_{i,n,t}, v^D_{i,n,n^2})$$

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

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

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

TODO: explain that these segments are in fact diagonal

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

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*

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

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

Proof. TODO: jakiś prosty z definicji

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*

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

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

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

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* $DIAG$*, then some spaces between neighbouring points were covered twice.*

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 covered with* $DIAG$*, then one of them had to be also covered with a segment from* HOR *(*VER*).*

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

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

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

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 between h^R_{i,j,t_1} and $h^L_{i,j+1,t_2}$, so $math_h(t_1, t_2)$ must be true.

3.3.3. What is missing

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 pararell 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 is 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-pararell 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 pararell, so there exists exactly one such point and any other line don'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 in 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.

Unfortunaly 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.

Chapter 5

Geometric Set Cover with polygons

5.1. State of the art

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

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

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

Chapter 6

Conclusions

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