

The Complexity of Finding Tarski Fixed Points

Master Thesis

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Nils Jensen

ADVISED BY

PROF. DR. BERND GÄRTNER

SEBASTIAN HASSELBACHER

Abstract

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Introduction

1

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The aim of this chapter is to introduce the complexity class **TNFP**, and some of its subclasses, in particular **PPAD**, **PLS** and **EOPL**. We will also introduce the **TARSKI** problem.

2.1 Total search problems

The study of complexity classes originally works with so-called *decision-problems*, which are the question of deciding on the membership in a set — also called a *language*. Now while these problems are interesting, real world questions or problem often ask for an explicit answer. For instance while deciding if a function has a global minimum is a decision problem, we are interested in actually finding this minimum, which is not a decision problem.

This is where so called *search problems* come into play:

Definition 2.1 — Search Problem.

A *search problem* is given by a relation $R \subset \{0, 1\}^* \times \{0, 1\}^*$. For a given *instance* $I \in \{0, 1\}^*$ the computational problem, to find a *solution* $s \in \{0, 1\}^*$, that satisfies: $(I, s) \in R$ or output “No” if no such s exists.

Now of course we can view these search problems as decision problems by looking at the corresponding decision problem given by the language:

$$\mathcal{L}_R = \{I \in \{0, 1\}^* \mid \exists s \in \{0, 1\}^* : (I, s) \in R\}$$

We can then ask the classical complexity questions about these search problems, i.e. whether these search problems are in **P**? **NP**? whether they are **NP**-Hard? One easily observes that search problems are always at least as hard as just deciding whether a solution exist. This is because solving a search problem also solves the underlying decision problem. This leads to the natural question: what if we remove the underlying decision problem? This can be done by guaranteeing that “No” is never a solution. We call these problems where every instance admits a solution *total search problems*.

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Notable such problems include deciding on whether a boolean formula can be satisfied or if a k -Clique exist in a given graph.

Even though as we will see it can be transformed into one

The “No” case can be encoded as some special binary string.

Definition 2.2 — Total search problems.

A *total search problem* is a search problem given by a relation $R \subset \{0, 1\}^* \times \{0, 1\}^*$, such that for every given instance $I \in \{0, 1\}^*$ there is a solution $s \in \{0, 1\}^*$, that satisfies: $(I, s) \in R$.

The complexity class **TNFP** as introduced in [1] is simply the class of all total search problems that lie in **NP**. Examples of **TNFP** problems are:

- ▶ FACTORING, the problem of finding the prime factors of a number,
- ▶ NASH, the problem of finding a nash equilibrium in a bimatrix game,
- ▶ MINIMIZE, the problem of finding the global minimum of a convex function.

Similarly to decision problem we can also define reduction inside **TNFP**.

Definition 2.3 — Reduction.

For two problem $R, S \in \mathbf{TNFP}$, we say that R *reduces* (many to one) to S if there exist polynomial time computable functions $f : \{0, 1\}^* \rightarrow \{0, 1\}^*$ and $g : \{0, 1\}^* \times \{0, 1\}^* \rightarrow \{0, 1\}^*$ such that for $I, s \in \{0, 1\}^*$: if $(f(I), s) \in S$ then $(I, g(I, s)) \in R$. This means that if s is a solution to an instance $f(I)$ in S , we can compute $g(I, s)$ a solution to an instance I in R .

[1]: Papadimitriou (1994), *On the complexity of the parity argument and other inefficient proofs of existence*

This means that **TNFP** can be seen as an intermediate class between **P** and **NP**, containing all search problems where a solution is guaranteed to exist, and where one can efficiently check the feasibility of a candidate solution.

Saying one can reduce R onto S can be understood as saying if one can solve S efficiently then I can solve R efficiently.

2.2 An excursion into Binary Circuits

TODO

2.3 Subclasses of TNFP

Because the existence of complete **FNP**-Problems in **TNFP** would imply **NP** = **coNP**, as described in [2]. Because this is a very unexpected outcome we cannot expect to find complete problems in **TNFP**. This means that we should use other tools to study the structure of **TNFP**.

One of the challenges is that **TNFP** is a so-called *semantic* class. By semantic class we mean a class for which it is difficult to check if that Turing Machine defines a language in this class. A *syntactic* class is a class for which it is easy to check that the accepted language of a Turing Machine indeed belongs to the class. These

[2]: Megiddo et al. (1991), *On total functions, existence theorems and computational complexity*

Examples of syntactic classes include **P** and **NP**.

terms are defined in more detail in [3]. Hence we want to study syntactic subclasses of **TNFP**. One of the proposed methods [1] is to categorize total search problems with respect to the existence results which allow them to be *total*. This is what leads to the complexity classes we will discuss next.

[3]: Papadimitriou (1994), *Computational complexity*

[1]: Papadimitriou (1994), *On the complexity of the parity argument and other inefficient proofs of existence*

Polynomial Local Search (PLS)

The existence results which gives rise to **PLS** is “every directed acyclic graph has a sink”. We can then construct the class **PLS** by defining it as all problems which reduce to finding the sink of a directed acyclic graph (DAG).

Formally we first define the problem **LOCALOPT** as in [4]:

LOCALOPT

Input: Two binary circuits $P, S : [2^n] \rightarrow [2^n]$.

Output: A vertex $v \in [2^n]$ such that $P(S(v)) \geq P(v)$.

[4]: Johnson et al. (1988), *How easy is local search?*

S can be seen as a proposed successor, and P as a potential. The goal is to find a local minima v of the potential.

One might ask why this is equivalent to finding the sink of a DAG? The circuit S defines a directed graph, which might contain cycles. Only keeping the edge on which the potential decreases (strictly) leads to a DAG, with as sinks exactly the v such that $P(S(v)) \geq P(v)$. Now we can define **PLS**:

Definition 2.4 – Polynomial Local Search (PLS).

The class **PLS** is the set of all **TNFP** problems that reduce to **LOCALOPT**.

One of the reasons we think that studying very “easy” problems such as **PLS** is that we strongly believe that there is no clever way of solving these problems without actually walking through the graph. Hence if we have a graph of exponentially large size it seems very unlikely that one can find an efficient way of solving the problem. Hence all problems in **PLS** can be thought of as including the fundamental difficulty of not being able to do better than to walk along some graph.

By “easy” we mean that the problem can be solved by simply walking through the graph, and checking whether every vertex is a local minima.

Polynomial Parity Argument on Directed Graphs (PPAD)

Now we want to discuss the complexity class **PPAD**, introduced by Papadimitriou as one of the first syntactic subclasses of **TNFP** in [1]. The existence result giving rise to this class is that “If a directed graph has an unbalanced vertex, then it has at least one other unbalanced vertex”. **PPAD** can be defined using the problem **END-OF-LINE** as introduced in [5].

[1]: Papadimitriou (1994), *On the complexity of the parity argument and other inefficient proofs of existence*

[5]: Daskalakis et al. (2009), *The Complexity of Computing a Nash Equilibrium*

END-OF-LINE

Input: Boolean circuit $S, P : \{0, 1\}^n \rightarrow \{0, 1\}^n$ such that $P(0^n) = 0^n \neq S(0^n)$ (0^n is a source.)

Output: An $x \in \{0, 1\}^n$ such that either:

- ▶ $P(S(x)) \neq x$ (x is a sink) or
- ▶ $S(P(x)) \neq x \neq 0^n$ (x is a non non-standard source)

Here S can be thought of giving the successor of a vertex, and P as giving the predecessor of a vertex.

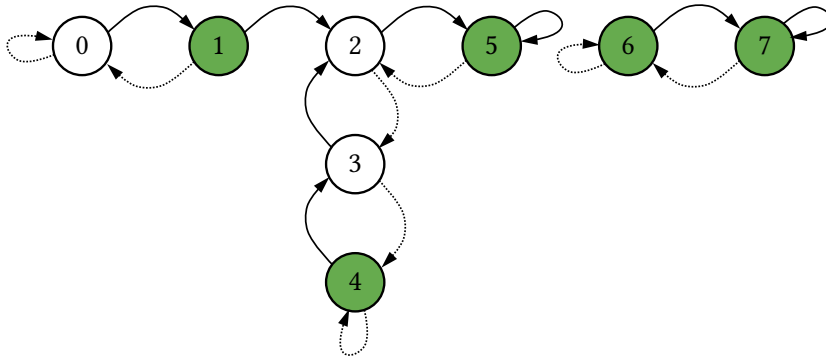


Figure 2.1: Example of an END-OF-LINE Problem with $n = 3$ (8 vertices). The circuit S is represented by solid lines and the circuit P by dashed lines. The solutions are the sinks $x = 5$, $x = 7$ and $x = 1$, as well as the sources $x = 4$ and $x = 6$.

These boolean circuits represent a directed graph with maximal in and out degree 1, by having an edge from x to y if and only if $S(x) = y$ and $P(y) = x$. The goal is to find a sink of the graph, or another source. It can be shown that the general case of finding a second imbalanced vertex in a directed graph (a problem called IMBALANCE) can be reduced to END-OF-LINE [6]. Now we can define the complexity class **PPAD** as follows:

Definition 2.5 – PPAD.

The class **PPAD** is the set of all **TNFP** problems that reduce to END-OF-LINE.

Notice that END-OF-LINE allows cycles, and that these do not induce solutions.

[6]: Goldberg et al. (2021), *The Hairy Ball problem is PPAD-complete*

End of Potential Line (EOPL)

Next we want to discuss the complexity class **EOPL** as introduced in [7]. The existence results which gives rise to **EOPL** is that “in a directed acyclic graph, there must be at least two unbalanced vertices”. Similarly to **PLS** acyclicity will be enforced using a potential.

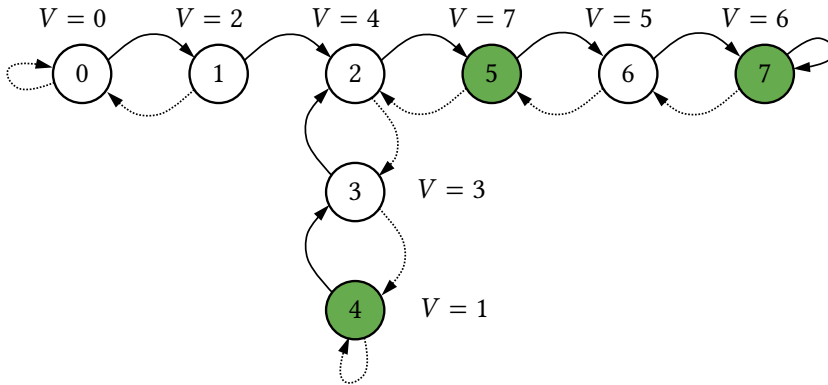
[7]: Fearnley et al. (2018), *End of Potential Line*

END OF POTENTIAL LINE

Input: Two boolean circuits $S, P : \{0, 1\}^n \rightarrow \{0, 1\}^n$, and a boolean circuit $V : \{0, 1\}^n \rightarrow [2^n - 1]$, such that 0^n is a source, (i.e. $P(0^n) = 0^n \neq S(0^n)$).

Output: An $x \in \{0, 1\}^n$ such that either:

- ▶ $P(S(x)) \neq x$ (x is a sink)
- ▶ $S(P(x)) \neq x \neq 0^n$ (x is a *non-standard source*)
- ▶ $S(x) \neq x$, $P(S(x)) = x$ and $V(S(x)) \leq V(x)$ (violation of the monotonicity of the potential)



Here S can be thought of giving the successor of a vertex, and P as giving the predecessor of a vertex. V can be thought of as a potential which is supposed to be monotonously increasing along the line.

Figure 2.2: Example of an EOPL Problem with $n = 3$ (8 vertices). The circuit S is represented by solid lines and the circuit P by dashed lines. The solutions are the sink $x = 7$, the violation of potential at $x = 5$ and the non-standard source $x = 4$.

S and P can be thought of as representing a directed line. Finding another source (a non-standard source), is a violation, as a directed line only has one source. The potential serves a guarantee of acyclicity. Now we can define the complexity class **EOPL**.

Definition 2.6 — EOPL.

The class **EOPL** is the set of all **TNFP** problems that reduce to **END OF POTENTIAL LINE**.

2.4 The TARSKI Problem

Next we want to introduce the **TARSKI** Problem. Before we do this we recall that there is a partial order on the d dimensional lattice $[N]^d$, given by $x \leq y$ iff $x_i \leq y_i$ for all $i \in \{1, \dots, d\}$. The name originates from **TARSKI**'s fixed point Theorem as introduced in [8] which we remind the reader of below:

Theorem 2.1 — Tarski's fixed point Theorem.

Let $f : [N]^d \rightarrow [N]^d$ a function on the d -dimensional lattice. If f is monotonous (with respect to the previously discussed partial order), then f has a fixed point, i.e. there is an $x \in [N]^d$ such that $f(x) = x$.

[8]: Tarski (1955), A lattice-theoretical fixpoint theorem and its applications.

This theorem is also known as the Knaster–Tarski Theorem in the literature.

A proof of this theorem can be found in the previously mentioned work [8]. Without surprise the TARSKI problem as defined in [9], is now to find such a fixed-point. Formally we define the problem as follows:

TARSKI

Input: A boolean circuit $f : [N]^d \rightarrow [N]^d$.

Output: Either:

- ▶ An $x \in [N]^d$ such that $f(x) = x$ (fixed point) or
- ▶ $x, y \in [N]^d$ such that $x \leq y$ and $f(x) \not\leq f(y)$ (violation of monotonicity).

[9]: Etessami et al. (2020), *Tarski's Theorem, Supermodular Games, and the Complexity of Equilibria*

This is of course a total search problem, as there will always either be a fixed point, or a point violating monotonicity. We now want to summarize where TARSKI lies inside of **TNFP**. It has been shown in [9] that TARSKI lies in both **PLS** and $\mathbf{P}^{\mathbf{PPAD}}$. Previous work [10], showed that many-to-one reductions and Turing-reduction onto **PPAD** are equivalent. In particular this means that $\mathbf{P}^{\mathbf{PPAD}} = \mathbf{PPAD}$, and that TARSKI also lies in **PPAD**.

[10]: Buss et al. (2012), *Propositional proofs and reductions between NP search problems*

2.5 Structure of $\mathbf{PLS} \cap \mathbf{PPAD}$

Now that we have established that TARSKI lies inside $\mathbf{PLS} \cap \mathbf{PPAD}$, we want to discuss the structure of $\mathbf{PLS} \cap \mathbf{PPAD}$ and describe recent advances in the study of this class.

Reducing TARSKI onto PPAD

In this chapter we will discuss how one can reduce TARSKI onto **PPAD**. We will do this by discussing the currently known proof of this reduction on high level, and then rephrasing the problem by introducing a new problem TARSKI*. This will help us use a divide and conquer strategy to solve TARSKI by solving TARSKI* and also allow to give a new proof of **PPAD** membership of TARSKI by reducing TARSKI* onto **PPAD** using SPERNER'S LEMMA, instead of the original proof using Brouwer's Fixed Point Theorem. This will give us insights for a further reduction of TARSKI* onto **EOPL** in the next chapter.

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3.1 Presentation of the know reduction of TARSKI onto PPAD

Previous work has established that TARSKI lies in **PPAD**, as shown in [9]. We want to give a high level presentation of this proof, which will help us motivate the introduction of TARSKI* and the subsequent use of SPERNER'S LEMMA. The proof given by Etessami et al. relies on BROUWER'S FIXED POINT THEOREM, which we introduce below.

[9]: Etessami et al. (2020), *Tarski's Theorem, Supermodular Games, and the Complexity of Equilibria*

Theorem 3.1 — Brouwer's fixed point theorem.

Let $K \subset \mathbb{R}^d$ be a compact, convex set. Then every continuous function $f : K \rightarrow K$ has a fixed point $x^* \in K$, i.e. $f(x^*) = x^*$.

The original proof can be found in [11], a simpler proof relying on SPERNER'S LEMMA can be found in [12]. This theorem gives rise to a total search problem which we call BROUWER:

[11]: Brouwer (1911), *Über Abbildung von Mannigfaltigkeiten*

[12]: Aigner et al. (2018), *Proofs from THE BOOK*

BROUWER

Input: A continuous function $f : K \rightarrow K$.

Output: A fixed point $x^* \in K$ such that $f(x^*) = x^*$.

We leave out the technical detail of how this function is given using boolean circuits, and how precise the output needs to be, as it is not relevant for this high level presentation.

[13]: Papadimitriou (1994), *On the complexity of the parity argument and other inefficient proofs of existence*

The problem BROUWER was first introduced in [13], and was shown to be **PPAD**-complete. This means that it suffices to reduce TARSKI onto BROUWER in order to show that TARSKI is in **PPAD**. We will actually reduce TARSKI onto at most polynomially many instances of BROUWER, which will allow us to show that TARSKI is in P^{PPAD} .

The idea of the the proof is to extend the discrete function f , to a function $\tilde{f} : [0, 2^n - 1]^d \rightarrow [0, 2^n - 1]^d$, such that \tilde{f} interpolates

the lattice function f , is continuous and piecewise linear between lattice points, and hence continuous. This can be achieved using a simplicial decomposition of the each cell of the lattice. Now we have an instance of BROUWER, and hence we can find a fixed point x^* of \tilde{f} . Of course this fixed point does not need to be *integral*. The key insight is that we can use this fixed point to reduce the search area for a integral fixed point by at least half, or find a violation of monotonicity. In particular either there is a fixed point in $\{x \in [2^n - 1]^d : x \geq x^*\}$ and $\{x \in [2^n - 1]^d : x \leq x^*\}$. Or there is a violation of monotonicity in the cell containing x^* . We can repeat this procedure always halving the search area, which allows us to solve a TARSKI instance using at most $\mathcal{O}(d \cdot n)$ calls to BROUWER. This concludes the proof that TARSKI is in \mathbf{P}^{PPAD} . The result follows from the fact that PPAD is closed under polynomial time reductions [10].

We call a point *integral* if it belongs to the original lattice.

[10]: Buss et al. (2012), *Propositional proofs and reductions between NP search problems*

3.2 Introducing TARSKI*

In the previous section we have seen that TARSKI can be reduced onto a polynomial number of BROUWER instances. We would like to study a single such reduction, in order to give an alternative proof that TARSKI is in PPAD. In order to do this we introduce a new problem, TARSKI*. This problem can be thought of, as a subproblem in order to solve TARSKI, as we will argue. A standard strategy to solve TARSKI is to use a *divide and conquer* strategy, as for instance in [9]. We want to construct a problem, which allows us to divide the TARSKI problem into two smaller problems, where solving the smaller of the two leads to a solution. We propose the following problem:

[9]: Etessami et al. (2020), *Tarski's Theorem, Supermodular Games, and the Complexity of Equilibria*

For the sake of generality and for the proofs in the following we introduce the problem on a general lattice $L = N_1 \times \dots \times N_d$, such that $N_i \leq 2^n$.

TARSKI*

Input: A boolean circuit $f : L \rightarrow L$.

Output: Either:

(T*1) Two points $x, y \in L$ such that $\|x - y\|_\infty \leq 1$, $x \leq f(x)$ and $y \geq f(y)$, or

(T*2) A violation of monotonicity: Two points $x, y \in L$ such that $x \leq y$ and $f(x) \not\leq f(y)$.

We now want to show that TARSKI* can be seen as a subproblem of TARSKI.

Claim 3.1

An instance of TARSKI can be solved using $\mathcal{O}(d \cdot n)$ calls of TARSKI* and up to $\mathcal{O}(d)$ additional steps.

Proof. We will show that we can use a single call of TARSKI* to either find a violation of monotonicity, a fixpoint, or an instance of TARSKI which has at most half as many points, and must contain a solution. We proceed by case distinction:

Case 1: If $x = y$, then x is a fixpoint, and we are done.

Case 2: If either $f(x) = x$ or $f(y) = y$, then we are done, because we have found a fixpoint.

Case 3.1: If $x < y$ and $f(x) \not\leq f(y)$, we have a violation of monotonicity, which solves the given TARSKI instance.

Case 3.2: If $x < y$ and $f(x) \leq f(y)$, we claim that we can solve the TARSKI instance in $\mathcal{O}(\|x - y\|_1)$ additional function calls. Notice that x and y can be thought of as being vertices on the same hypercube of length 1, because $\|x - y\|_\infty \leq 1$. Now notice that because $f(x) > x$ (if not see case 2), there is at least one dimension $i \in \{1, \dots, d\}$ such that $f(x)[i] > x[i]$. Also notice that in this dimension i if $f(y)[i] < y[i]$, then because $|x[i] - y[i]| \leq \|x - y\|_\infty \leq 1$, we would have a violation of the monotonicity of f in this dimension. Therefore we must have $f(y)[i] = y[i]$. The same argument shows that if in any dimension j $f(y)[j] < y[j]$, then $f(x)[j] = x[j]$. Therefore we know that because there must be at least one such dimension i and j we have:

$$\|f(x) - f(y)\|_\infty \leq \|x - y\|_\infty \leq 1 \quad \text{and} \quad \|f(x) - f(y)\|_1 \leq \|x - y\|_1 - 2$$

Hence we can now repeat the same argumentation with $f(x)$ and $f(y)$, and we can do this at most $\mathcal{O}(\|x - y\|_1)$ times, until we find a violation of monotonicity or a fixpoint. Because $\|x - y\|_1 \leq d$, this will take at most $\mathcal{O}(d)$ additional steps.

Case 4: If $x \not\leq y$, then we can partition the set of lattice points into two sets S_x and S_y , as follows:

$$S_x = \{z \in L : z \geq x\} \quad \text{and} \quad S_y = \{z \in L : z \leq y\}.$$

These two sets are disjoint: if there was a $z \in S_x \cap S_y$, then $x \leq z \leq y$, which would imply $x \leq y$, which is a contradiction. We will show that S_x must contain a solution to the TARSKI instance. If for some $z \in S_x$ we have $f(z) \notin S_x$, then we have $f(z) \not\leq f(x)$, because or else we have $f(z) \leq f(x) \leq x$, which contradicts the assumption, hence x, z are two points witnessing a violation of monotonicity of f . This means that S_x forms a new valid instance of TARSKI. By the same argumentation S_y also forms a valid instance of TARSKI and hence it suffices to solve the smaller of the two instances. In particular because they are disjoint, one of the instances S_x or S_y contains less than half of the lattice points of L , and hence we can solve the instance in $\mathcal{O}(\log 2^{dn}) = \mathcal{O}(d \cdot n)$ calls of TARSKI*. \square

We do not actually need to check these points, it suffice to have the algorithm stop if at any point it notices that f leaves S_x .

3.3 SPERNER'S Lemma

Of course the previous discussions assumes, that TARSKI* is a total problem, that is, that every instance has a solution, which we will prove in this section, in order to conclude that that TARSKI* is in **TNFP**. Instead of using BROUWER'S THEOREM, a tool from continuous topology, we want to use it's discrete counterpart, SPERNER'S LEMMA, which is a combinatorial result. This seems natural for two reasons:

- ▶ We are working on a discrete lattice, and hence it seems more natural to use a discrete tool.
- ▶ Papadimitriou proved that BROUWER is **PPAD**-complete by reducing BROUWER onto SPERNER in [13]. Hence by reducing onto Brouwer, we introduce continuity into the problem, which is not necessary.

[13]: Papadimitriou (1994), *On the complexity of the parity argument and other inefficient proofs of existence*

We now introduce Sperner's Lemma, which was first proven in [14], a more modern proof can be found in [12].

[14]: Sperner (1928), *Neuer beweis für die invarianz der dimension-zahl und des gebietes*

Theorem 3.2 – Sperner's Lemma.

Suppose that a d -dimensional simplex with vertices v_0, \dots, v_d is subdivided into smaller simplices (in 2 dimensions this is a triangulation). Now color every vertex with a color $\{0, \dots, d\}$ such that v_i is colored i , and the vertices on a subsimplex $\{v_{i_0}, \dots, v_{i_k}\}$ are colored with colors i_0, \dots, i_k . Then there is a subsimplex, such that all colors are used.

[12]: Aigner et al. (2018), *Proofs from THE BOOK*

We give an example of a 2-dimensional simplex, which is subdivided into smaller simplices, and colored according to SPERNER'S Lemma in TODO.

Next we introduce the problem SPERNER, which is a total search problem, that was introduced and shown to be **PPAD**-complete in [13].

[13]: Papadimitriou (1994), *On the complexity of the parity argument and other inefficient proofs of existence*

SPERNER

Input: A coloring $c : L \rightarrow \{0, \dots, d\}$ of the vertices of L , such that for every $i \in \{0, \dots, d\}$ the the vertices $\{x \in L : x[i] = 0\}$ are not colored i .

Output: A cell C such that for all $i \in \{0, \dots, d\}$ there is a vertex $x \in C$ such that $c(x) = i$.

We define Sperner on a euclidian lattice for convenience, but it can be defined on any simplicial decomposition of the space.

A presentation of why construction can be seen as a simplicial decomposition of a d -dimensional simplex, and the coloring as a coloring of the vertices of the simplex can also be found in [13].

For us to be able to use SPERNER'S Lemma, on our TARSKI* instances, we need to define a coloring of the vertices of L . We

propose the following coloring $l : L \rightarrow \{0, \dots, d\}$:

$$c(x) = \begin{cases} 0 & \text{if } x \leq f(x) \\ 1 & \text{else if } x[1] > f(x)[1] \\ \vdots & \\ d & \text{else if } x[d] > f(x)[d] \end{cases}$$

A vertex colored 0 indicates that the function points *forwards* in all dimensions, a vertex colored i for $i \geq 1$ indicates that the function points *backwards* in at least the i -th dimension.

We now need two results. First we need to show that a cell with all colors always exists, which will allow us to show that TARSKI* is a total search problem. Second we need to show that finding a cell with all colors, yields a solution to TARSKI*, in polynomial time.

The first result, follows directly from SPERNER'S Lemma, and the coloring we have defined. There can never be a vertex colored i with $x[i] = 0$, because this would imply that $f(x)[i] \leq x[i]$, which is a contradiction to the construction of the function. Hence by dividing each cell of the lattice into simplices, we can apply SPERNER'S Lemma to show that a cell with all colors always exists. The vertices we use as the vertices of the large simplex are $\{(0, \dots, 0), (2^n - 1, 0, \dots, 0), \dots, (0, \dots, 2^n - 1)\}$. Now we can advance to the second part:

Claim 3.2

Finding a cell with all colors, yields a solution to TARSKI*, in $\mathcal{O}(d)$ steps.

Proof. Assume we have found a simplex, with vertices colored $0, \dots, d$. Let us denote x_i the vertex colored i , for $i \in \{0, \dots, d\}$. Notice that all of these vertices are by construction contained in some cell (hypercube of length 1), let $\mathbf{0}$ be the smallest vertex of this hypercube and $\mathbf{1}$ the largest. In particular this means that for all i we have:

$$\mathbf{0} \leq x_i \leq \mathbf{1} \quad \text{and} \quad f(x_i)[i] < x_i[i] \quad \text{for } i > 0$$

We now proceed by case distinction:

Case 1: If x_0 is a fixed point, then $x = y = x_0$ is a solution to TARSKI*.

Case 2: If $x_0 \neq f(x_0)$ and $x_0 = \mathbf{0}$. Then there is an i such that $f(x_0)[i] > x_0[i]$, which means that $f(x_0)[i] - x_0[i] \geq 1$. At the same time we must have $f(x_i)[i] < x_i[i]$ and $x_0[i] - x_i[i]$ because $x_0 = \mathbf{0}$,

and hence $x_i[i] - f(x_i)[i] \geq 1$. Now we get:

$$f(x_0)[i] - f(x_i)[i] = \underbrace{f(x_0)[i] - x_0[i]}_{\geq 1} + \underbrace{x_0[i] - x_i[i]}_{\geq 0} + \underbrace{x_i[i] - f(x_i)[i]}_{\geq 1}$$

$$f(x_0)[i] - f(x_i)[i] \geq 2$$

This implies that $f(x_0) \not\leq f(x_i)$, and hence x_0, x_i are two points witnessing a violation of monotonicity of f , which form a solution to TARSKI*.

Case 3: If $x_0 \neq f(x_0)$ and $x_0 \neq \mathbf{0}$. We claim that either $f(\mathbf{0}) \leq \mathbf{0}$, or we have a violation of monotonicity. Assume for the sake of contradiction that there is an i such that $f(\mathbf{0})[i] > \mathbf{0}[i]$. Then we must have $f(x_i)[i] < x_i[i]$ hence we get: $f(\mathbf{0})[i] \not\leq f(x_i)[i]$, which is a violation of monotonicity. This means that either we can return $y = x_0$ and $x = \mathbf{0}$ as a solution to TARSKI*, or x_i and $\mathbf{0}$ as a violation of monotonicity. \square

APPENDIX

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