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Traveling salesmen in the presence of competition

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Abstract

We propose the "competing salesmen problem" (CSP), a two-player competitive version of the classical traveling salesman problem. This problem arises when considering two competing salesmen instead of just one. The concern for a shortest tour is replaced by the necessity to reach any of the customers before the opponent does.

In particular, we consider the situation where players take turns, moving along one edge at a time within a graph $G=(V,E)$. The set of customers is given by a subset $V_C \subseteq V$ of the vertices. At any given time, both players know of their opponent's position. A player wins if he is able to reach a majority of the vertices in V_C before the opponent does.

We prove that the CSP is PSPACE-complete, even if the graph is bipartite, and both players start at distance 2 from each other. Furthermore, we show that the starting player may not be able to avoid losing the game, even if both players start from the same vertex. However, for the case of bipartite graphs, we show that the starting player always can avoid a loss. On the other hand, we show that the second player can avoid to lose by more than one customer, when play takes place on a graph that is a tree T, and V_C consists of leaves of T. It is unclear whether a polynomial strategy exists for any of the two players to force this outcome. For the case where T is a star (i.e., a tree with only one vertex of degree higher than two) and V_C consists of n

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leaves of T, we give a simple and fast strategy which is optimal for both players. If V_C consists not only of leaves, we point out that the situation is more involved.

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1. Introduction

In the classical traveling salesman problem (TSP), we are given a (weighted) graph $G=(V,E)$ and the task to find a shortest roundtrip that visits every vertex precisely once. This reflects the situation where a salesman has to visit a set of customers and return to his initial position.

However, a salesman may be confronted with competitors who are eager to sign up the same clientele—giving a new twist to the old motto "first come, first serve".

This situation motivates the "*competitive salesmen problem*" (CSP).

We are given a (directed or undirected) road system, i.e., a graph $G=(V,E)$ and the locations of the customers, i.e., a subset $V_C \subseteq V$ of the vertices. There are two players, I and II, with starting positions v_I and v_{II}, and an initial score of zero. Starting with I, both players take turns moving by changing from the current location to an adjacent vertex. Depending on the scenario, players may or may not be allowed to pass. At any given time, both players know of their own and their opponent's position as well as about all the remaining vertices with customers. If a player reaches a vertex with a customer, his score is increased by one, and the vertex is removed from the set V_C of still available customers, but not removed from V. The game ends when no further customers can be captured, i.e., when $V_C=\emptyset$ or when no player has a path to an uncaptured customer. Whoever has a higher score at the end of the play, wins. If both players end up with the same score, the game is tied.

An immediate generalization is to consider two competing teams of salesmen; in the CSP(h,k), a move of player I consists of moving one of his h pieces, while player II has the choice between one of his k pieces.

2. Preliminaries

The CSP is a *combinatorial game*. See [2,6] for classical references on this well-studied area, and [3–5,7] for other related papers. Here we just note an important distinction for the outcome of games that are not won by either player.

A game that is won neither by I nor by II is called

- *tied*, if it ends with both players having the same score,
- *drawn*, if it does not end.

Throughout this paper, we mostly concentrate on the case of an undirected graph. Some of the results include the directed case, but we do point out some additional difficulties in one interesting case. Throughout the paper, there are a number of illustrations; in these figures, the set $V_C \subseteq V$ is indicated by circled dots. Without loss of generality, we assume that a start vertex never belongs to V_C; in several cases, a start vertex is indicated by a hexagon.

The rest of this paper is organized as follows. In Section 3, we show that the CSP is PSPACE-complete, even for the case of bipartite undirected graphs, with both players starting at distance 2 from each other. In Section 4, we discuss the situation in which both players start from the same vertex. We show that even in this case, player I may not be able to avoid a loss, and that there may be draws. We also show that in the case of bipartite graphs, player I can avoid a loss. We also show that this result does not apply to directed graphs. In Section 5, we give some results and open problems for the special case of trees, and Section 6 considers the further restriction to trees with only one vertex of degree higher than two.

3. Complexity

While the TSP on directed or undirected graphs is merely NP-complete, the two-player competitive game CSP turns out to be PSPACE-complete.

Theorem 1. *The decision problem whether player* I *can win in* CSP$(1,1)$ *is* PSPACE-*complete, even for the special case of bipartite graphs, with both players starting at distance* 2 *from each other.*

Proof. A *position* in CSP(h,k) is a quintuple $(\tau, G, V'_C, u_I, u_{II})$, where $\tau \in \{I, II\}$ indicates whether Player I or Player II moves from the position, $G=(V,E)$ is the (di-)graph on which the game is played, V'_C is the current set of uncaptured customers; and u_I and u_{II} are the vertices on which players I and II reside. A draw can be declared after a position is repeated, that is, when a new position is encountered which is identical to a previous one. Identical positions can be detected by sequentially storing all the positions from the position at which V'_C was last diminished until it decreases again, beginning with the original V_C. If there are h and k salesmen for the two sides, at most $O(n^{h+k})$ positions have to be stored between any two consecutive changes of V'_C, where $n=|V|$. If h and k are fixed, this is of polynomial size in the input size, in particular, if $h=k=1$. Therefore, for fixed h and k, CSP$(h,k) \in$ PSPACE.

To see that CSP$(1,1)$ is PSPACE-hard, we describe a reduction from quantified 3SAT (Q3SAT), where the Boolean formula F, containing m clauses and n variables, is in conjunctive normal form with three literals per clause.

For technical reasons, and without loss of generality, we shall make the following assumptions.

(1) The number n of variables is even; because otherwise we may postfix F with $\forall x_{n+1} \exists x_{n+2} \forall x_{n+3}\ (x_{n+1} + \bar{x}_{n+1} + x_{n+2})(\bar{x}_{n+2} + x_{n+3} + \bar{x}_{n+3})$.

(2) There is a clause which contains a true literal and a false literal for every truth assignment of the variables; because if such a clause does not exist, then we can postfix F with $\exists x_{n+1} \forall x_{n+2}\ (x_{n+1} + \bar{x}_{n+1} + x_{n+2})(x_{n+1} + x_{n+2} + \bar{x}_{n+2})$.

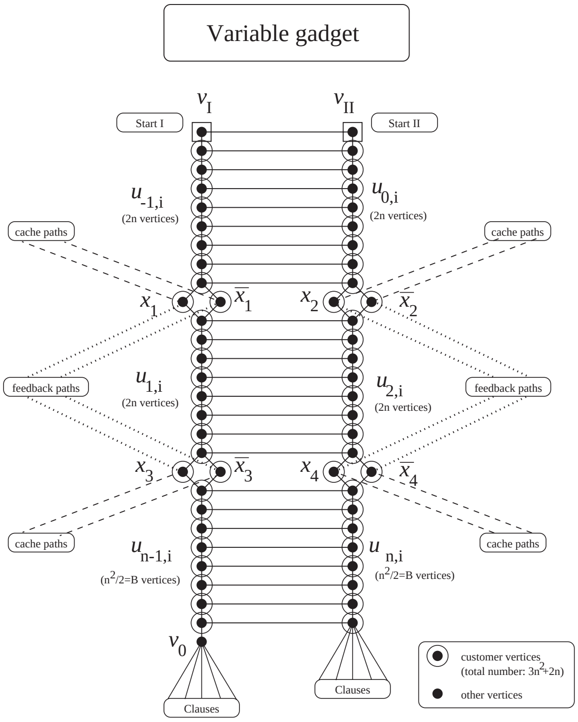

Fig. 1. The variable gadget: player I chooses a truth setting for the odd variables by running from v_{I} to $u_{n-1,B}$, while player II chooses a truth setting for the even variables by running from v_{II} to $u_{n,B}$.

From a given instance of Q3SAT, we construct an instance of CSP$(1,1)$ by specifying the graph $G=(V,E)$ on which it is played. For simplicity and clearer drawings, we first construct a graph that contains some odd cycles in the subgraphs representing the clauses. It is straightforward to turn this graph into a bipartite one, by subdividing all the original edges, in effect doubling all distances.

We proceed to describe G by listing all vertices and edges of the construction. In the following, we use $B:=n^2/2$ for simpler notation. Different parts of the construction are shown in Fig. 1 for the variable gadget, in Fig. 2 for the m clause gadgets, and in Fig. 3 for a cache gadget.

$$
\begin{aligned}
V = \{&x_i, \bar{x}_i\colon\ 1 \leqslant i \leqslant n\}\\
&\cup\{v_{\mathrm{I}}, v_{\mathrm{II}}\}\\
&\cup\{u_{i,h}\colon\ -1 \leqslant i \leqslant n-2, 1 \leqslant h \leqslant 2n\}\\
&\cup\{u_{i,h}\colon\ n-1 \leqslant i \leqslant n, 1 \leqslant h \leqslant B\}\\
&\cup\{v_j, a_j, b_j, c_j, y_j^1, y_j^2, y_j^3\colon\ 1 \leqslant j \leqslant m\}
\end{aligned}
$$

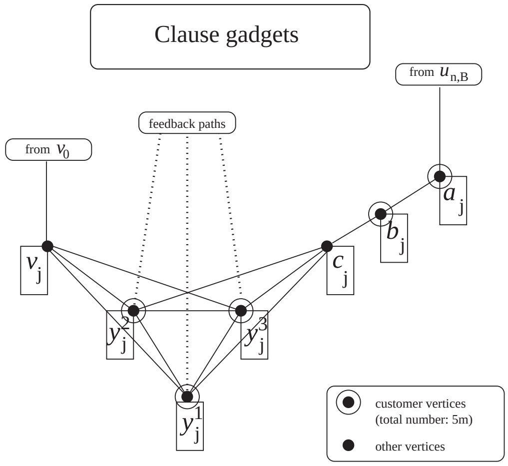

Fig. 2. A clause gadget: player II picks up two customers at a_j and b_j, while player I collects two of the customers at y_j^k, leaving the third y_j^k to player II. The outcome of the game is decided by the possibility of picking up an extra customer on a variable, after traveling back to the variable gadget along a feedback path.

$$
\begin{aligned}
&\cup\{v_0\}\\
&\cup\{p_{j,h}^k\colon\ 1 \leqslant k \leqslant 3, 1 \leqslant j \leqslant m, 1 \leqslant h \leqslant B-n\}\\
&\cup\{q_{i,h}\colon\ 0 \leqslant i \leqslant 2n, 1 \leqslant h \leqslant n^3\}\\
&\cup\{d_i\colon\ 0 \leqslant i \leqslant 5m+n-6\}.\\
E = {}&\{(v_{\mathrm{I}}, v_{\mathrm{II}}), (v_{\mathrm{I}}, u_{-1,1}), (v_{\mathrm{II}}, u_{0,1})\}\\
&\cup\{(u_{i,h}, u_{i,h+1})\colon\ -1 \leqslant i \leqslant n-2, 1 \leqslant h \leqslant 2n\}\\
&\cup\{(u_{i,h}, u_{i,h+1})\colon\ n-1 \leqslant i \leqslant n, 1 \leqslant h \leqslant B\}\\
&\cup\{(u_{i,2n}, x_{i+2}), (u_{i,2n}, \bar{x}_{i+2})\colon\ -1 \leqslant i \leqslant n-2\}\\
&\cup\{(x_i, u_{i,1}), (\bar{x}_i, u_{i,1})\colon\ 1 \leqslant i \leqslant n\}\\
&\cup\{(u_{2i+1,h}, u_{2i+2,h})\colon\ -1 \leqslant i \leqslant n/2-1, 1 \leqslant h \leqslant 2n\}\\
&\cup\{(u_{n-1,h}, u_{n,h})\colon\ 1 \leqslant h \leqslant B\}\\
&\cup\{(u_{n-1,B}, v_0)\}\\
&\cup\{(u_{n,B}, a_j), (v_0, v_j), (a_j, b_j), (b_j, c_j)\colon\ 1 \leqslant j \leqslant m\}\\
&\cup\{(y_j^1, y_j^2), (y_j^1, y_j^3), (y_j^2, y_j^3)\colon\ 1 \leqslant j \leqslant m\}
\end{aligned}
$$

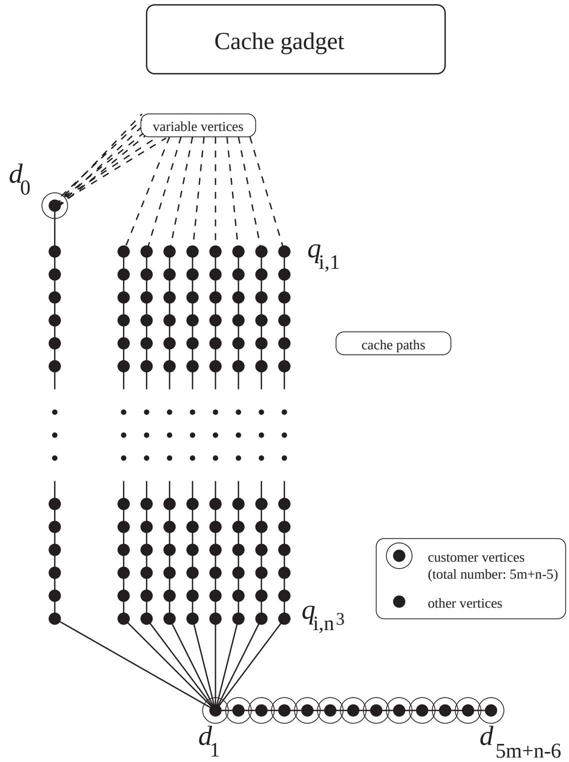

Fig. 3. The cache gadget: A set of $5m + n - 6$ customers very far from the rest of the graph, allowing a player to claim the victory if he has collected enough customers on the main part of the graph. The additional node d_0 breaks a tie in favor of player I iff player I wins the corresponding instance of Q3SAT.

$$\cup\{(v_j, y_j^k), (c_j, y_j^k)\colon\ 1 \leqslant k \leqslant 3, 1 \leqslant j \leqslant m\}$$

$$\cup\{(y_j^k, p_{j,1}^k)\colon\ 1 \leqslant k \leqslant 3, 1 \leqslant j \leqslant m\}$$

$$\cup\{(p_{j,h}^k, p_{j,h+1}^k)\colon\ 1 \leqslant k \leqslant 3, 1 \leqslant j \leqslant m, 1 \leqslant h \leqslant B - n\}$$

$$\cup\{(p_{j,B-n}^k, x_i)\colon\ \text{iff } c_j \text{ contains } x_i \text{ as literal } k,$$

$$1 \leqslant k \leqslant 3,\ 1 \leqslant i \leqslant n, 1 \leqslant j \leqslant m\}$$

$$\cup\{(p_{j,B-n}^k, \bar{x}_i)\colon\ \text{iff } c_j \text{ contains } \bar{x}_i \text{ as literal } k,$$

$$1 \leqslant k \leqslant 3,\ 1 \leqslant i \leqslant n, 1 \leqslant j \leqslant m\}$$

$$\cup\{(x_i, q_{2i,1}), (\bar{x}_i, q_{2i-1,1}), (x_i, d_0), (\bar{x}_i, d_0)\colon\ 1 \leqslant i \leqslant n\}$$

$$\cup\{(q_{i,h}, q_{i,h+1})\colon\ 0 \leqslant i \leqslant 2n, 1 \leqslant h \leqslant n^3 - 1\}$$

$$\cup\{(d_0, q_{0,1})\}$$

$$\cup\{(q_{i,n^3}, d_1):\ 0 \leqslant i \leqslant 2n\}$$

$$\cup\{(d_h, d_{h+1}):\ 1 \leqslant h \leqslant 5m+n-6\}.$$

We single out the subset of V on which customers reside:

$$V_C = \{x_i, \bar{x}_i:\ 1 \leqslant i \leqslant n\}$$

$$\cup\{a_j, b_j, y_j^1, y_j^2, y_j^3:\ 1 \leqslant j \leqslant m\}$$

$$\cup\{u_{i,h}:\ -1 \leqslant i \leqslant n-2, 1 \leqslant h \leqslant 2n\}$$

$$\cup\{u_{i,h}:\ n-1 \leqslant i \leqslant n, 1 \leqslant h \leqslant B\}$$

$$\cup\{d_i:\ 0 \leqslant i \leqslant 5m+n-6\}.$$

The initial vertices for players I and II are v_{I} and v_{II}, respectively. Note that $|V| = 2n + 2 + 2n^2 + 2B + 7m + 1 + 3m(B-n) + 2n^4 + 5m + n - 5 = 2n^4 + 3mn^2/2 + 3n^2 - 3mn + 12m + 3n - 4$, $|V_C| = 2n + 5m + 2n^2 + 2B + 5m + n - 5 = 3n^2 + 10m + 3n - 5$. The construction is clearly polynomial. An example with $n = 4$ is depicted in Fig. 1. (Note that this yields $2n = 8 = n^2/2 = B$.) A clause gadget is shown in Fig. 2. To avoid cluttering the figure, some of the edges connecting the *diamonds* (the subgraphs induced by $(u_{i-2,2n}, x_i, \bar{x}_i, u_{i,1})$) with other parts of the construction are only shown symbolically. Fig. 3 shows the structure of the remaining part. The vertices $p_{j,h}^k$ induce a collection of *feedback paths* that connect the *triangles* (y_j^1, y_j^2, y_j^3) in the gadget representing clause j to the variable representations of the literals y_j^1, y_j^2, and y_j^3.

It will be useful to designate the subgraph of G induced by $q_{0,1}, \ldots, q_{2n,n^3}$, $d_0, d_1, \ldots, d_{5m+n-6}$ as the *cache part* $G_2 = (V_2, E_2)$ of G, and the subgraph of G induced by $V \setminus V_2$ as the *main part* $G_1 = (V_1, E_1)$.

Remark. (a) We have $|V_C \cap V_2| = 5m + n - 6$, $|V_C \cap V_1| = 3n^2 + 5m + 2n + 1$, and a player wins by collecting at least $3n^2/2 + 5m + 3n/2 - 2$ customers.

(b) Moving from the main part to the cache part takes longer than visiting all vertices of the main part.

(c) In the proof, we shall see that in every play on G, all the customers are captured. Only after capturing at least $3n^2/2 + n/2 + 4$ customers in the main part can a player win by moving to the cache part. For by (a), $(3n^2/2 + n/2 + 4) + 5m + n - 6 = 3n^2/2 + 5m + 3n/2 - 2 = \lfloor |V_C/2| \rfloor + 1$. Thus, a player who captured precisely $3n^2/2 + n/2 + 4$ customers in the main part and then goes for the cache part before the opponent starts to do so wins by at least one customer.

Here is the "regular" play on G. We shall see later that "small" deviations are compatible with regular play, but "large" deviations lead to the defeat of the deviator.

The players move down their respective sides of the "ladders" formed by the $u_{i,h}$, and traverse the diamonds according to their chosen truth assignments in the given instance of Q3SAT, i.e., traversing x_i if $x_i = 1$, otherwise traversing $\bar{x}_i$. In this manner, player I gets to assign the "odd", i.e., existentially quantified, variables, while II gets to assign the "even", i.e., all-quantified, variables. After this stage, I makes the move $(u_{n-1,B}, v_0)$. Player II now selects a clause c_j by moving from x_n to a_j. This is matched by the move (v_0, v_j) of I. While II traverses b_j, c_j, player I selects the literal within c_j to which II should move. Player I enforces this by capturing the other two of the customers in the triangle $T_j = (y_j^1, y_j^2, y_j^3)$. Then II captures the remaining $y_j^{k_3}$. Following the feedback path incident to $y_j^{k_2}$, I takes $B - n$ moves to get to a suitable literal, say z_{i_2}, on one of the diamonds, and II takes the same number of moves from $y_j^{k_3}$ along its feedback path to a literal, say z_{i_3}, on a diamond.

At this stage, each of the players has captured $3n^2/2$ customers along the ladders, and $n/2$ customers on the diamonds; I has also captured two customers on the triangle T_j, and possibly a customer on z_{i_2}. Thus, I has captured $3n^2/2 + n/2$ plus 2 or plus 3 customers. Player II has captured two customers on a_j, b_j and one on T_j, possibly also one on z_{i_3}. Thus, II has now captured $3n^2 + n/2$ plus 3 or plus 4 customers.

Suppose first that II can win in the given instance of Q3SAT. This means that for any truth assignment of the variables of player I, player II can assign truth values so that at least one clause c_j is false, i.e., all the literals in c_j have value 0. In terms of regular play, this means that II captured a customer on z_{i_3}. Thus, II captured $3n^2/2 + n/2$ plus 4 customers, at least one more than player I. At this point I moves next. If I chooses to move straight to the cache part, player I will capture a total of at most $3n^2/2 + n/2 + 3 + 5m + n - 6 = 3n^2/2 + 5m + 3n/2 - 3 < |V_C|/2$. By restricting himself to the main part, II can capture all the rest, namely $3n^2/2 + 5m + 3n/2 - 2$, so II wins by precisely one customer. Therefore, player I will make some other move, e.g., the move (z_{i_2}, d_0). Then II responds by moving to the cache part. By Remark (c), II thus wins in the constructed instance of CSP$(1,1)$ by precisely one customer.

Secondly, suppose that player I can win in the given instance of Q3SAT. This implies that player I can assign truth values such that for any truth assignment of II, every clause contains at least one true literal. In terms of regular play on the constructed instance of CSP$(1,1)$, this means that player I can arrange that z_{i_3} will already have been captured during the initial diamond traversal, so II will have captured only $3n^2/2 + n/2 + 3$ customers up to and including the feedback edge traversal. We consider two cases.

(i) The clause c_j selected by II contains a false literal, say z_{i_ℓ}. Then I continues according to regular play, playing in the triangle T_j such that II is "forced" to move to z_{i_k}, and I himself moves to z_{i_ℓ}. Then player I will have captured $3n^2/2 + n/2 + 3$ customers, the same as II. It is now the turn of I. As above it is seen that if I moves immediately to the cache part, he loses by one customer. A better move for I is (z_{i_ℓ}, d_0). Now II cannot afford to let I take the cache, so II has to move $(z_{i_k}, q_{i_k,1})$. This allows I to take a remaining customer on a literal vertex, maintaining a distance of n^3 to the cache. Player II still has to guard the cache by limiting his distance from d_1 to at most $n^3 - 1$, and is thus forced to move

$(q_{i_k,1}, q_{i_k,2})$. Eventually, I picks up all remaining literal customers by going via d_0. In a similar manner, I can collect all remaining customers in the main part: First, I picks up all remaining customers at vertices y_j^k, which have distance $n^3 + B - n$ from the cache. This is possible without exceeding this distance; at the same time, II cannot afford to move to the same distance from the cache, as this would leave the cache unguarded. Next, I can move on to collecting the vertices b_j (which have distance $n^3 + B - n + 2$ from the cache) one by one, and finally collect the vertices a_j, which have distance $n^3 + B - n + 3$. At this point, I has won the game.

(ii) The clause c_j selected by II contains no false literal. Then I deviates slightly from regular play, by moving to a clause, say c_ℓ, which does contain a false literal z_{i_f}. Such a clause exists by assumption (3) above. After I captures two customers in T_ℓ, I moves to z_{i_f}, having thus far captured $(3n^2/2 + n/2) + 3$ customers. Then player I continues as in the case (i), winning. Note that the three paths leading out from c_j to the diamonds all end in literals whose customers have already been captured, and that I wins independently of whether II captures one, two or three customers in T_j.

We have shown that if the players stick to regular play, then player I can win in Q3SAT if and only if player I can win in CSP(1, 1). It remains to check non-regular play.

First of all, not proceeding down a ladder (say, to collect a customer at d_0 or at an additional literal vertex) takes at least two moves per additional customer. This lets the other player change over to the deviator's side of the ladder, continue in a zig-zagging fashion back and forth between both sides of and down the ladder, and thus continue to collect one customer per move. Therefore, the violator loses in the balance, compared to regular play. Furthermore, remark (c) above implies that if either player goes for the cache part at any point during the diamond traversal before having traversed a feedback edge, then that player loses, since a minimum of $3n^2/2 + n/2 + 4$ captures have to be made by a winning player in the main part prior collecting the cache.

If II loses in CSP(1, 1), II can possibly use a feedback edge leading back to a literal z_{i_ℓ} whose customer has not been captured during the diamond traversal, by using a vertex of T_j whose customer was already captured by I. But then the balance of customers captured by II up to the capture at z_{i_ℓ} is unchanged, and I still wins.

Conversely, if II wins in CSP(1, 1), player I might traverse a feedback edge after having captured only one customer on a triangle $T_{j'}$ (possibly $j' \neq j$), hoping to capture enough customers during a second traversal of the diamonds, before II will have captured enough. An easy accounting argument, left to the reader, shows that player I cannot muster a sufficient supply of customers with this maneuver. □

It is not hard to see that the above construction can be modified to establish a proof of the PSPACE-completeness of the CSP on bipartite directed graphs without antiparallel edges. Furthermore, it can be modified to cover the scenario in which both players move simultaneously: after scaling edge lengths by a factor of two, give Player I a headstart of one move.

4. Identical starting point

The result in the previous section shows that deciding the outcome of a CSP instance is quite difficult, even when both players start very close to each other, and the graph is bipartite. In this section, we concentrate on the natural special case in which both players start from the *same* vertex. As it turns out, this scenario is quite different.

Theorem 2. *For the CSP on bipartite graphs with both players starting at the same point, player* I *can avoid a loss.*

Proof. By way of contradiction, suppose player II has a winning strategy, and both players start from vertex v_0. Now suppose I moves to vertex v_1^{I}, and II can counter this move by v_1^{II}. In the following, let I visit any sequence of vertices $v_1^{\mathrm{I}}, v_2^{\mathrm{I}}, v_3^{\mathrm{I}}, \ldots$ By assumption, II has a winning strategy, so there is a sequence of moves $v_1^{\mathrm{II}}, v_2^{\mathrm{II}}, v_3^{\mathrm{II}}, \ldots$ that ends with II capturing an absolute majority of customers. Note that each v_i^{II} is determined by the sequence $v_1^{\mathrm{I}}, v_2^{\mathrm{I}}, v_3^{\mathrm{I}}, \ldots, v_i^{\mathrm{I}}$; by induction, we can write $v_i^{\mathrm{II}}(v_i^{\mathrm{I}})$ to indicate that I's move to v_i^{I} was successfully countered by II by moving to v_i^{II}.

Now consider, for any sequence $u_1^{\mathrm{II}}, u_2^{\mathrm{II}}, u_3^{\mathrm{II}}, \ldots$ of moves by II, the following sequence of moves for I:

$$v_1^{\mathrm{I}}, v_0, v_1^{\mathrm{II}}(u_1^{\mathrm{II}}), v_2^{\mathrm{II}}(u_2^{\mathrm{II}}), v_3^{\mathrm{II}}(u_3^{\mathrm{II}}), \ldots \ .$$

This means that player I gives up two moves by moving to any neighbor v_1^{I} and back to v_0, thereby giving player II a head start of $1\ \frac{1}{2}$ moves. Then I plays against a "phantom player" II$'$ that is one move lagging behind the real player II, i.e., precisely $\frac{1}{2}$ move ahead of I, which allows I to "steal" the assumed second player's strategy against such a player.

By assumption, the above is a well-defined sequence of moves for I. Therefore, player I wins more than half of the customers against II$'$, but II wins more than half of the customers against I. Hence, there must be a customer (say, at vertex v_*) that I reaches before II$'$, but that II reaches before I. Therefore, I must be moving to vertex v_* when II is already there, and just before II$'$ gets there.

This is a contradiction to the bipartiteness of G: After a move of I, both players must always occupy vertices of opposite color, so *I* cannot reach v_* with II positioned on that vertex.

Therefore, II cannot have a winning strategy, proving the claim. □

Note that the theorem remains valid for directed graphs, if there is a single pair of anti-parallel edges that allows I to leave and return to v_0 in just two moves.

The following example (courtesy of David Wood) shows that the possibility of moving back to v_0 is crucial for the proof: In the absence of an undirected edge at v_0, player I may be limited to winning a single customer.

Theorem 3. *There is a family of instances of CSP on directed graphs in which* I *cannot win more than* 1 *out of* n *customers.*

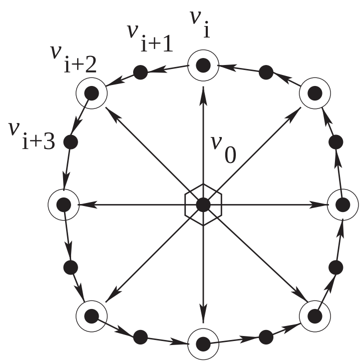

Fig. 4. Player I loses by $n-1$ customers.

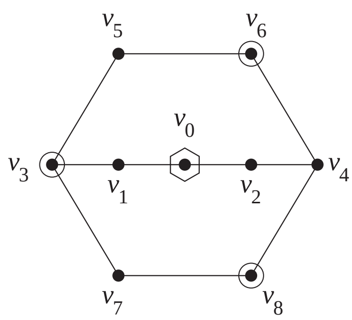

Fig. 5. Player I loses.

Proof. Consider the graph shown in Fig. 4. The initial vertex for both players is denoted by v_0, the vertex set V_C is indicated by the circled vertices.

Suppose I starts by moving to vertex v_i; then II responds by moving to vertex v_{i+2}. Now the rest of the game is determined, and I only wins the customer at v_i. □

For non-bipartite graphs, I may lose, even on undirected graphs, provided passing is not allowed.

Theorem 4. *There are instances where* I *cannot avoid a loss*, *even if both players start from the same vertex.*

Proof. Consider the graph shown in Fig. 5. The initial vertex for both players is denoted by v_0, the vertex set V_C is indicated by the three circled vertices.

Player I is in a zugzwang situation: Suppose I starts by moving to vertex v_1; then II moves to vertex v_2. If then I moves back to v_0, II moves on to v_4; it is straightforward to check that now II will force a win by taking the customer at v_6 and at least one

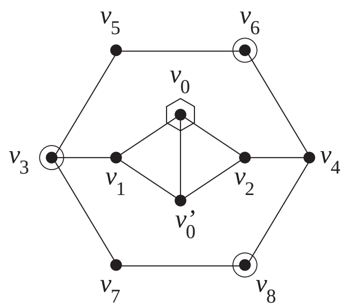

Fig. 6. A draw game.

of v_3 and v_8. Hence, we can assume that I's second move is to v_3. However, this is answered by II by moving to v_4, and I cannot prevent II from taking both v_6 and v_8.

Therefore, consider the case where I starts by moving to v_2; II responds by moving to v_1. As in the previous case, II wins by moving to v_3 if I moves back to v_0. Hence, we can assume that I's second move is to v_4, followed by II moving to v_3, securing the first customer. Regardless of I's next move, II can again force a win by taking at least one of the remaining two customers.

This concludes the proof. □

An immediate consequence is the following.

Theorem 5. *There are instances where optimal play from both* I *and* II *forces a draw, even if both players start from the same vertex.*

Proof. Consider the graph shown in Fig. 6. The initial vertex for both players is denoted by v_0, the vertex set V_C is indicated by the three circled vertices.

Suppose player X is the first to move to one of the vertices in $\overline{V} = \{v_1, v_2\}$, while the other player Y has not left the vertex set $\{v_0, v_0'\}$. Then the analysis of Theorem 4 shows that player Y can force a win by moving to the other vertex in $\overline{V}$.

Therefore, neither of the players is willing to leave the set $\{v_0, v_0'\}$, resulting in a draw. □

5. Trees

Our proof of Theorem 2 is purely existential. Furthermore, there is still no proof that player I cannot just avoid a loss, but also avoid a draw, and end the game with a win or a tie.

Conjecture 6. *For the CSP on trees, one of the players can force a win or a tie.*

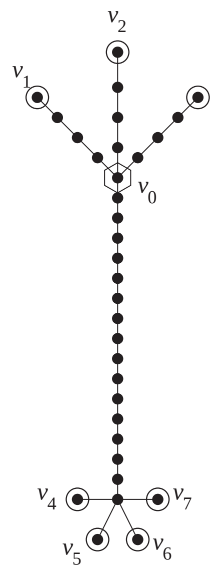

Fig. 7. Player I can only win when accepting to trail by a large number.

In particular, this implies that for the case of identical starting point and an odd number of customers, player I always wins the game.

We have a pretty good idea how to tackle this problem; a constructive argument may use bookkeeping on subsets of customers, and the number of moves necessary to collect them and return to a previous position. (This means generalizing the idea of playing against a phantom player, and arguing that on trees it can only be an advantage to have extra moves to spare.) We hope to finish this argument at a later time. But even if this works out, the resulting construction is exponential in size and rather awkward. It would be a lot more satisfying to have a simple strategy that guarantees a win for player I.

However, there are a number of difficulties that are indicated by the following observations.

Theorem 7. *There are instances of CSP on trees, with both players starting from the same vertex* v_0, *the number of customers being* $2k+1$, *and the only way for player* I *to win allows* II *to potentially collect k customers before* I *reaches even a single customer.*

Proof. Consider the graph shown in Fig. 7. It has k customers at an intermediate distance from the starting vertex v_0, and at twice that distance from each other. Furthermore, there is a cluster of $k+1$ customers at a large distance from v_0, but at a small distance from each other.

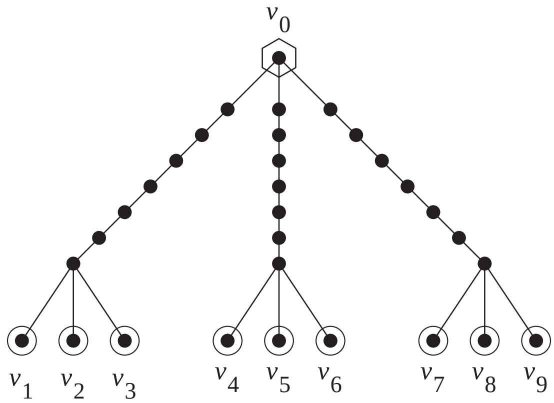

Fig. 8. Player I loses when adapting an a priori strategy.

If I starts by taking one of the nearer customers, II collects all the distant customers and wins. On the other hand, II may take all the near customers before I takes one of the distant ones. □

Theorem 8. *Consider instances of CSP on trees, where both players start on the same vertex v_0. In general, player* I *cannot avoid a loss by adapting an a priori strategy, i.e., by prioritizing the customers in an appropriate way, and always trying to collect the customer with the highest priority.*

Proof. Consider the graph shown in Fig. 8. It consists of a symmetric tree with nine customers at the leaves, grouped into three triples.

Without loss of generality, assume that v_1 is the first customer on I's list; furthermore, assume that v_4 is the first customer on the list that is none of v_1, v_2, v_3. Then it is straightforward to check that II can collect the customers v_5, v_6, v_7, v_8, v_9 without any interference from I, thus winning the game: In order to win, I would be forced to visit customers from all three different clusters, which takes longer than II needs to collect all five customers. □

Finally, player II can limit his losses in a natural special case. A rather involved argument for the following can be found in the fourth author's thesis. We omit this proof, as we believe that there should be a relatively simple argument; in particular, a proof of Conjecture 6 as described should do the trick.

Theorem 9. *Consider an instance of the CSP where the graph G is a tree T and both players start at the same vertex v_0. Suppose all customers are positioned at leaves of the tree. Then player* II *can avoid a loss by more than one customer. In particular,* II *can avoid a loss when the number of customers is even.*

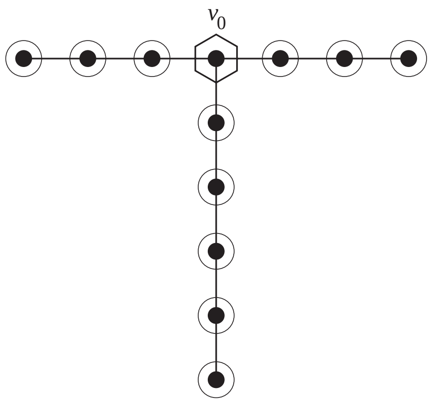

Fig. 9. Can you give a *simple* winning strategy for player I, and a short proof that it wins?

6. Stars

It may be easier to come up with a strategy for the class of CSP instances in which the graph G is a star, i.e., a tree T with at most one vertex of degree higher than two. Again, we consider both players starting from the same vertex. If customers are only contained in leaves, it is not hard to see that there is a simple optimal strategy for both players, by always choosing the nearest free customer when returning to the central node.

However, it is straightforward to see that the example in Fig. 9 cannot be won using this approach: If I collects all five customers along the longest ray, II gets all customers along the other two rays. Similarly, it follows that I loses when trying to pick up all the customers along a single ray. We leave it to the reader as an exercise to work out a winning strategy for this instance.

7. Conclusions

In this paper, we have introduced the CSP. Many open problems remain. Besides the ones mentioned directly or indirectly throughout the paper, there are many more. One of the more interesting scenarios may be a continuous geometric version, in which customers are points in some space of fixed dimension, and the players move continuously or in discrete portions along arbitrary paths. Clearly, this introduces additional difficulties.

As there are innumerable variants of the TSP, due to many different practical constraints, requirements, or objective functions, it is quite conceivable that there are many more related games. One such variant (called the freeze tag problem, FTP) has been considered in [1], where a set of cooperating players have to awake each other, and any awake player can awake a sleeping player by moving next to him. In the original game of freeze tag, there are two competing teams, and one wins if it can freeze all opposing players, while the second one tries to avoid this permanently.

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