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To cite this version:
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The Plane Subgraph Completion problem asks, given a (possibly disconnected) plane graph $\Gamma$ and a connected plane graph $\Delta$, whether it is possible to add edges in $\Gamma$ such that the resulting graph remains planar and contains some subgraph that is topologically isomorphic to $\Delta$. We give an algorithm that solves this problem in $2^{O(k \log k)} \cdot n^2$ steps where $k$ and $n$ are the number of vertices of $\Delta$ and $\Gamma$ respectively.

1 Introduction

Completion problems are defined as follows: Consider a graph class $\mathcal{P}$ and ask whether we may add edges to a given graph $G$ in order to obtain a graph $G^+$, where $G^+ \in \mathcal{P}$. Numerous results have appeared for the case where the objective is to minimize the number of added edges \cite{12, 9, 10, 8, 4} in $G$. However, interestingly there is no known dichotomy asserting when the problem is solvable in polynomial time and when it is NP-complete.

In this paper, we consider the Plane Subgraph Completion (PSC) problem which, given a (possibly disconnected) plane graph $G$ and a connected plane graph $H$, asks whether it is possible to add edges in $G$ such that the resulting graph remains planar and contains some subgraph that is topologically isomorphic to $H$. When the input graph $G$ is planar triangulated, PSC is NP-complete. Indeed, let $G$ be any planar triangulated graph. Note here, that as any planar triangulated graph is 3-connected, $G$ is 3-connected and from Whitney’s Theorem \cite{11} admits a unique embedding on the plane (up to equivalence). Let also $H$ be the cycle on $n = |V(G)|$ vertices. Then $H$ also has unique embedding on the plane (up to equivalence). Since $G$ is triangulated no edge can be added to it while preserving its planarity. Thus, PSC becomes equivalent to the HAMILTON CYCLE PROBLEM which is NP-complete on planar triangulated graphs \cite{6} (see also \cite{7}). This observation further implies that PSC parameterized by the number of added edges $k$, and in particular even for $k = 0$, is NP-complete. Thus, PSC is not FPT when parameterized by the number of added edges unless $P = NP$. Thus, in order to obtain a tractable algorithm, we need to find an alternative way to parameterize this problem. In particular, we will consider $|V(H)|$ as our parameter. Such alternative parameterization first appeared in \cite{3}.

To state our main result, and throughout the paper, we need the following definitions.

*The first and the fourth authors were supported by the E.U. (European Social Fund - ESF) and Greek national funds through the Operational Program “Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) - Research Funding Program: “Thales. Investing in knowledge society through the European Social Fund”. The third author was supported by the FP7-PEOPLE-2013-CIG project CountGraph (ref. 630749), and the Berlin Mathematical School.
Plane graphs and completion subgraphs By plane graph \( \Gamma \) we mean a planar graph \( \Gamma \) with the vertex set \( V(\Gamma) \) and the edge set \( E(\Gamma) \) drawn in the sphere. To simplify notations, we usually do not distinguish between a vertex of the graph and the point of the sphere used in the drawing to represent the vertex or between an edge and the open line segment representing it. We define the following relation on plane graphs. Let \( \Gamma \) and \( \Delta \) be plane graphs. We say that \( \Delta \preceq \Gamma \) if there exists a set \( S \in (V(\Gamma)) \setminus E(\Gamma) \) such that \( \Gamma' = (V(\Gamma), E(\Gamma) \cup S) \) is plane and \( \Delta \) is topologically isomorphic to a subgraph of \( \Gamma' \). Notice that \( \preceq \) is not a transitive relation.

Our main result is the following.

**Theorem 1.** There exists an algorithm that, given as input an \( n \)-vertex plane graph \( \Gamma \) and a connected \( k \)-vertex plane graph \( \Delta \) decides whether \( \Delta \preceq \Gamma \) in \( 2^{O(k \log k)} \cdot n^2 \) steps.

Let \( \Gamma \) and \( \Delta \) be an input of PSC as above. In order to obtain our algorithm we consider a family \( \mathcal{G} \) consisting of \( n \) structures depending only on \( \Gamma \) whose underlying graphs have treewidth at most \( 3k \) (Lemma 6). We also consider a family \( \mathcal{D} \) consisting of \( 2^{O(k)} \) structures depending only on \( \Delta \) (Lemma 4). For the graphs \( \Gamma \) and \( \Delta \) and the families \( \mathcal{G} \) and \( \mathcal{D} \), it holds that \( \Delta \preceq \Gamma \) if and only if some structure \( \mathcal{D} \in \mathcal{D} \) is contained as a special contraction in a structure \( \mathcal{G} \in \mathcal{G} \), denoted \( \mathcal{D} \preceq \mathcal{G} \) (Lemmata 5 and 7). Finally, for a fixed pair of structures \( (\mathcal{D}, \mathcal{G}) \in \mathcal{D} \times \mathcal{G} \), we can decide in \( 2^{O(k \log k)} \cdot n \) time whether \( \mathcal{D} \preceq \mathcal{G} \) (Lemma 2). Therefore, by testing for all pairs \( (\mathcal{D}, \mathcal{G}) \in \mathcal{D} \times \mathcal{G} \) whether \( \mathcal{D} \preceq \mathcal{G} \), we decide in \( 2^{O(k \log k)} \cdot n^2 \) steps whether \( \Delta \preceq \Gamma \).

2 Preliminaries

**Contractions** A *structure* \( \mathcal{G} \) is a tuple whose first element is a graph \( G \) and the rest of its elements are subsets of \( V(G) \) forming a partition of \( V(G) \). Let \( \mathcal{G} = (G, S_0, Y, S_1, S_2, S_3, S_4) \) and \( \mathcal{D} = (D, Z_0, B, Z_1, Z_2, Z_3, Z_4) \) be structures. We say that \( \mathcal{D} \) is a *contraction* of \( \mathcal{G} \), denoted by \( \mathcal{D} \preceq \mathcal{G} \), if and only if there exists a function \( \sigma : V(G) \to V(D) \) such that:

1. if \( u, v \in V(D), u \neq v \iff \sigma^{-1}(u) \cap \sigma^{-1}(v) = \emptyset \),
2. for every \( u \in V(D), G[\sigma^{-1}(u)] \) is connected,
3. \( \{u, v\} \in E(D) \iff G[\sigma^{-1}(u) \cup \sigma^{-1}(v)] \) is connected,
4. for every \( i \in \{0, \ldots, 4\} \) and every \( x \in Z_i \) it holds that \( |\sigma^{-1}(x)| = 1 \) and \( \sigma^{-1}(x) \in S_i \), and
5. \( \sigma(Y) \subseteq B \).

We say that a graph \( G \) is a *contraction* of a graph \( D \) if \( (D, \emptyset, \emptyset, \emptyset, \emptyset, \emptyset) \leq_c (G, \emptyset, \emptyset, \emptyset, \emptyset, \emptyset) \) and we denote it by \( D \leq_c G \). Notice that \( \leq_c \) defined for graphs is the usual contraction relation where only conditions 1, 2, and 3 apply.

The next Lemma follows using the results in [2].

**Lemma 2.** There exists an algorithm that receives as input a structure \( \mathcal{G} \), whose graph has \( n \) vertices and treewidth at most \( h \), and a structure \( \mathcal{D} \), whose graph is connected and has \( k \) vertices, and outputs whether \( \mathcal{D} \leq_c \mathcal{G} \) in \( 2^{O(k + h + k \log h)} \cdot n \) steps.

**Radial enhancements** Let \( \Gamma \) be a plane graph. A *radial enhancement* of \( \Gamma \) is defined as a plane graph that can be constructed as follows: take \( \Gamma \), add a vertex \( v_f \) inside each face \( f \) of \( \Gamma \) and add edges connecting \( v_f \) with the vertices incident to \( f \), so that in the resulting embedding, every face that is incident to an edge of \( E(\Gamma) \) is triangulated (this triangulation
may have multiple edges). We denote by $R_Γ$ the set of all different (in terms of topological isomorphism) radial enhancements of $Γ$. Observe that if $Γ$ is connected, then $R_Γ$ contains only one member that will be denoted as $R(Γ)$.

Given a connected plane graph $Γ$, we define $Q(Γ) = R(sub(R(Γ)))$, where $sub(Γ)$ is the graph obtained from $Γ$ if we subdivide all its edges once.

If $Γ$ and $Γ'$ are plane graphs such that $Γ' = Q(Γ)$ and $S \subseteq V(Γ)$, then we denote by $p(Γ, Γ', S) = (S_0, S_1, S_2, S_3, S_4)$ where $S_0 = S$ and:

\[
\begin{align*}
S_1 &= V(Γ) \setminus S_0 \\
S_2 &= V(R(Γ)) \setminus (S_0 \cup S_1) \\
S_3 &= V(sub(R(Γ))) \setminus (S_0 \cup S_1 \cup S_2) \\
S_4 &= V(Q(Γ)) \setminus (S_0 \cup S_1 \cup S_2 \cup S_3)
\end{align*}
\]

Also given a tuple $p$ of sets of vertices of a plane graph $Γ$ and a set $Q \subseteq V(Γ)$, we define $t(p, Q) = (Q, p \setminus Q)$, where the operation $p \setminus Q$ removes from each element of $p$ the vertices in $Q$. And if $G = (G, S_0, S_1, S_2, S_3, S_4)$, then we define $r(G) = (G, S_0, ∅, S_1, S_2, S_3, S_4)$.

3 The algorithm

**Lemma 3.** Let $Γ$ and $Δ$ be plane graphs. If $Δ$ is topologically isomorphic to a subgraph of $Γ$ then for every $Γ \in R_Γ$ there exists some $Δ_0 \in R_Δ$ such that $Q(Γ)$ is isomorphic to $Q(Δ_0)$.

A face extension of a connected plane graph $Δ$ is a connected plane supergraph $Δ^+$ of $Δ$ such that $V(Δ^+) \setminus V(Δ)$ is an independent set and $N_{Δ^+}(x) ≠ N_{Δ^+}(y)$, for every $x, y \in V(Δ^+) \setminus V(Δ)$ with $x ≠ y$, where $N_{Δ^+}(x)$ is the neighbourhood of the vertex $x$ in $Δ^+$. We then denote by $F_Δ$ the set of all face extension of the connected plane graph $Δ$.

Given a plane graph $Δ$ and $L \subseteq E(Δ)$, we denote by $span(Δ, L)$ the set of all spanning subgraphs of $Δ$ that contain all edges in $E(Δ) \setminus L$.

**Lemma 4.** If $Δ$ is a connected plane $k$-vertex graph, then $|F_Δ|, |span(Δ, E(Δ))| \leq 2^{O(k)}$.

Based on Lemma 3, we prove the following:

**Lemma 5.** Let $Γ$ be a plane graph and $Δ$ a connected plane graph. It holds that $Δ \leq Γ$ if and only if there exists some $Δ^+ \in F_Δ$ such that there exists some $Δ^* \in span(Δ^+, E(Δ))$ such that for every $Γ \in R_Γ$ there exists a $R_Δ^* \in R_Δ^*$ such that

\[
(Q(R_Δ^*), t(p(Q(R_Δ^*), R_Δ^*, V(Δ^*)), V(Δ))) \leq_c (Q(Γ), r(p(Q(Γ), R_Γ, V(Γ)))).
\]

Given a structure $G = (G, S_0, ∅, S_1, S_2, S_3, S_4)$, a non-negative integer $k$ and a vertex $v \in S_0$, we define $G_v^{(k)} = (G_v', S_0' \setminus Y, S_1', S_2', S_3', S_4')$ such that $G_v'$ is the graph created from $G$ if for every $C \in C(Δ)$, the set of all the connected components of $G$, we contract all edges of $C$ to a single vertex $v_C$, where $G_v' = G \setminus B_G^k(v)$, and $B_G^k(v)$ is the set of all the vertices at distance at most $k$ in $G$ from $v$. Also $Y = \{v_C | C \in C(Δ)\}$ and for $i \in \{0, \ldots, 4\}$, $S_i' = S_i \cap B_G^k(v)$.

The following is a direct consequence of [5].

**Lemma 6.** If $G = (G, S_0, ∅, S_1, S_2, S_3, S_4)$ is a structure, $k$ is a non-negative integer and $v \in V(G)$, then the graph of $G_v^{(k)}$ has treewidth at most $3k$.

**Lemma 7.** Let $G = (G, S_0, ∅, S_1, S_2, S_3, S_4)$ and $D = (D, Z_0, B, Z_1, Z_2, Z_3, Z_4)$ be two structures. Then $D \leq_c G_v^{(|V(D)|)}$.
Theorem 1 follows combining Lemmata 2, 4, 5, 6, and 7:

Theorem 1. Given an encoding of two plane graphs $\Gamma$ and $\Delta$, the question is: Is it true that $\Delta \bowtie \Gamma$?

1. for every $\Delta^+ \in F_\Delta$
2. for every $\Delta' \in \mathrm{span}(\Delta^+, E(\Delta))$
3. for every $u \in V(\Gamma)$
4. arbitrarily construct an $R_\Gamma \in R_\Gamma$
5. for every $R_\Delta^* \in R_\Delta^*$
6. construct $Q(\Gamma^n_u(V(\Delta)))$ and $Q(\Delta^*)$
7. if $Q(\Delta^*) \leq c Q(\Gamma^n_u(V(\Delta)))$, return true
8. return false

$\Gamma$ and $\Delta$ are the graphs with the black and red edges, red edges represent a choice in $\mathrm{span}(\Delta^+, E(\Delta))$. Greyed vertices are added by the first radial enhancement. $\sigma$ maps black vertices to black, grey to grey and blue regions to blue vertices.

4 Conclusion

We can drop the number of steps to $2^{O(k)} \cdot n^2$ by using the results of [1] and [2]. Our approach can also solve the PLANE INDUCED SUBGRAPH COMPLETION problem where we are asked, given a plane graph $G$ and a connected plane graph $H$, whether it is possible to add edges in $G$ such that the resulting graph remains planar and contains some induced subgraph that is topologically isomorphic to $H$. The only modification would be at the definition of a face extension of $\Delta$ where we would additionally require that every connected graph $\Delta^+$ contains $\Delta$ as an induced subgraph.

References