Graph Coloring and the Immersion Order*

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Abstract. The relationship between graph coloring and the immersion order is considered. Vertex connectivity, edge connectivity and related issues are explored. These lead to the conjecture that, if G requires at least t colors, then G must have immersed within it K_t, the complete graph on t vertices. Evidence in support of such a proposition is presented. For each fixed value of t, there can be only a finite number of minimal counterexamples. These counterexamples are characterized based on Kempe chains, connectivity, cutsets and degree bounds. It is proved that minimal counterexamples must, if any exist, be both 4-vertex-connected and t-edge-connected.

1 Introduction

The applications of graph coloring are legion. The usual goal, and the one we consider here, is to assign colors to vertices so that no two adjacent vertices are given the same color. Graph coloring has a long and storied history. The study of four-coloring planar graphs alone has generated interest for over 150 years [21]. Despite all this effort, graph coloring in general remains a notoriously difficult combinatorial problem.

The chromatic number of G, denoted by $\chi(G)$, is the minimum number of colors required by G in any proper coloring of its vertices. Of course it is well known that determining $\chi(G)$ is $\mathcal{NP}$-hard. It is tempting to try to associate $\chi(G)$ with some sort of clique contained within G. After all, if G contains K_t as a subgraph, then it is easy to show that G can be colored with no fewer than t colors. To see that the presence of a K_t subgraph is not necessary, however, one needs only to observe that C_5, the cycle of order five, requires three colors yet does not contain K_3 as a subgraph.

Nevertheless, perhaps some weaker form of K_t is present. One possibility is topological containment, in which taking subgraphs is augmented with removing subdivisions. An edge is subdivided when it is replaced by a path formed from two edges and an internal vertex of degree two; subdivision removal reverses this operation. For example, C_5 contains K_3 topologically. Sometime in the 1940s

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Hajós conjectured that if $\chi(G) \geq t$, then G must contain a topological K_t [11]. The conjecture is trivially true for $t \leq 3$. In 1952 Dirac proved it true for $t = 4$ [4]. It was not until Catlin's work in 1979 that Hajós' conjecture was finally settled, and negatively, with a family of counterexamples for $t \geq 7$ [3]. Ironically, one such counterexample is the 15-vertex graph defined by the crossproduct of C_5 and K_3. It requires eight colors but contains no topological K_8. Subsequently, Erdős and Fajtlowicz were able to prove the rather surprising result that almost all graphs are counterexamples [6]. Thus Hajós' conjecture remains open only for $t \in \{5, 6\}$.

Another possibility is the minor order, for which the allowable operations are taking subgraphs and contracting edges. The minor order is a generalization of the topological order, because subdivision removal is just a special case of edge contraction. Hadwiger conjectured in 1943 that, if $\chi(G) \geq t$, then G must contain a K_t minor [10]. This conjecture equates to Hajós' conjecture for $t \leq 4$. Wagner proved in 1964 that, for $t = 5$, it is equivalent to the four color theorem [26]. In 1993 Robertson, Seymour and Thomas proved it true for $t = 6$ [20]. Whether Hadwiger's conjecture holds true in general, however, has thus far not been decided. This is in spite of decades of research, hordes of supporting evidence and a multitude of results on many of its variants and restrictions [1, 5, 14, 23, 25, 27]. Even the celebrated Graph Minor Theorem [19] appears to shed no particular light on this question. As of this writing, a resolution of Hadwiger's conjecture seems distant.

In this paper we focus instead on the immersion order. A pair of adjacent edges uv and vw, with $u \neq v \neq w$, is lifted by deleting the edges uv and vw, and adding the edge uw. A graph H is said to be immersed in a graph G if and only if a graph isomorphic to H can be obtained from G by lifting pairs of edges and taking a subgraph. Previous investigations into the immersion order have generally been conducted from a purely algorithmic standpoint. We refer the reader to [2, 7–9, 17] for examples and applications. In contrast, here we mainly consider structural issues. We establish compelling connections between graph coloring and the immersion order, and conjecture that K_t is immersed in any graph requiring t or more colors.

2 Preliminaries

We restrict our attention to finite, simple undirected graphs (multiple edges and loops that may arise from lifting are irrelevant to coloring). G is said to be *t-vertex-connected* if at least t vertex-disjoint paths connect every pair of its vertices. A *vertex cutset* is a set of vertices whose removal breaks G into two or more nonempty connected components. The cardinality of a smallest vertex cutset in G is equal to the largest t for which G is t-vertex-connected (unless G is a complete graph, which can have no vertex cutset). G is said to be *t-edge-connected* if at least t edge-disjoint paths connect every pair of its vertices. An *edge cutset* is a set of edges whose removal breaks G into two or more nonempty connected components. The cardinality of a smallest edge cutset in G is equal to the largest t for which G is t-edge-connected.

If $\chi(G) \leq t$, then G is said to be *t-colorable*. If $\chi(G) = t$, then G is said to be *t-chromatic*. If $\chi(G) = t$ and $\chi(H) < t$ for every proper subgraph H of G, then G is said to be *t-color-critical*. A t-coloring of G is realized by a map c from the vertices of G to the set $\{1, 2, .., t\}$ so that, if G contains the edge uv, then $c(u) \neq c(v)$. Given such a map, c_{ij} is used to denote the subgraph induced by the vertex set $\{u : c(u) \in \{i, j\}\}$. A path contained within c_{ij} is termed a *Kempe chain* [28], so-named in honor of the foundational work done on them by Kempe in [15]. (Ironically, the main result in [15] was a purported proof of the Four Color Theorem that, like so many others, turned out to be fatally flawed.) Of course c_{ij} need not be connected, and so for any $u \in c_{ij}$ we employ $c_{ij}(u)$ to denote the set $\{v : v$ resides in the same connected component of c_{ij} as does $u\}$. Such sets have useful properties.

Observation 1. *If $\{i, j\} \neq \{k, l\}$, then c_{ij} and c_{kl} are edge disjoint.*

Although the immersion order is traditionally defined in terms of taking subgraphs and lifting pairs of edges, Kempe chains and Observation 1 make it helpful for us to utilize as well the following alternate characterization: H is immersed in G if and only if there exists an injection from the vertices of H to the vertices of G for which the images of adjacent elements of H are connected in G by edge-disjoint paths. Under such an injection, an image vertex is called a *corner* of H in G; all image vertices and their associated paths are collectively called a *model* of H in G.

We use $\delta(G)$ to denote the smallest degree found among the vertices of G. We use $N(u)$ to denote the neighborhood of u. Suppose u has degree $t - 2$ or less in a t-chromatic graph G. Then $G - u$ must also be t-chromatic. Otherwise $G - u$ could be colored with $t - 1$ colors, and u assigned one of the $t - 1$ colors unused within $N(u)$.

Observation 2. *If G is t-color-critical, then $\delta(G) \geq t - 1$.*

It is sometimes advantageous to select, restrict or manipulate colorings. For example, if G is t-chromatic but $G - u$ is only $(t-1)$-chromatic, then it is possible to consider only colorings in which u is assigned a unique color.

Observation 3. *If G is t-color-critical, then for any vertex u there exists a coloring c in which $c(u) = 1$ and $c(v) \neq 1$ for every vertex $v \in G - u$.*

Given the various connections between graph coloring, degrees and connectivity, and in turn the connections between connectivity and the immersion order, we seek to determine just how $\chi(G)$ is related to immersion containment. Our efforts to date prompt us to set the stage for this with the following conjecture. (A superficially similar conjecture has been made by Lescure and Meyniel [22]. Although sometimes called "the immersion conjecture," the notion of containment used there is not the immersion order.)

Conjecture *If $\chi(G) \geq t$, then K_t is immersed in G.*

This speculation motivates our work in the sequel. There we shall present what we believe is compelling preliminary evidence in its support. Our conjecture, like Hadwiger's, is trivially true for $t \leq 4$. This is because the immersion order generalizes the topological order, for which Hajós' conjecture is long known to hold when $t \leq 4$.

Before proceeding, we introduce a notion of immersion-criticality and show how it relates to the possible existence of counterexamples.

Definition *G is* t-immersion-critical *if $\chi(G) = t$ and $\chi(H) < t$ whenever H is properly immersed in G.*

Because $\chi(K_t) = t$, any counterexample must either be t-immersion-critical or have properly immersed within it another t-immersion-critical counterexample. Similarly, any t-immersion-critical graph distinct from K_t must be a counterexample. Thus our conjecture is equivalent to the statement that K_t is the only t-immersion-critical graph for every t. Although we have thus far fallen short of establishing this one way or the other, we can show that there are at most a finite number of them. To do this, we rely on properties of well-quasi-orders and immersion order obstruction sets. We refer the reader unfamiliar with these concepts to [7, 8, 16].

Theorem 1. *For each t, there are finitely many t-immersion-critical graphs.*

Proof. Consider the family of graphs $F = \{G : \chi(G) < t$ and $\chi(H) < t$ for every $H \leq_i G\}$. Then, by definition, F is closed in the immersion order. Because graphs are well-quasi-ordered by the immersion relation, it follows that F's obstruction set is finite. This set contains precisely the t-immersion-critical graphs. □

3 Main Results

Graph connectivity has long been a central feature of attempts to settle Hadwiger's conjecture. G is said to be *t-minor-critical* if $\chi(G) = t$ and $\chi(H) < t$ whenever H is a proper minor of G. K_t is of course both $(t-1)$-vertex-connected and $(t-1)$-edge-connected. Thus, if any t-minor-critical graph is not as strongly connected, then Hadwiger's conjecture is false for all $t' \geq t$. So suppose G denotes a t-minor-critical graph other than K_t (in which case the conjecture fails). Some 35 years ago [18], Mader showed that G must be at least 7-vertex-connected whenever $t \geq 7$. This provides evidence in support of the conjecture for $t \in \{7, 8\}$. A few years later [23], Toft proved that G must also be t-edge-connected. This provides additional supporting evidence for all t. Very recently, Kawarabayashi has shown that G must be at least $\lceil \frac{t}{3} \rceil$-vertex-connected as well [13]. Following this approach, we study both the vertex and edge connectivity of t-immersion-critical graphs. We assume $t \geq 5$ unless stated otherwise. Kempe chains play a pivotal role in our investigation.

3.1 Vertex Connectivity

Because they are t-color-critical, it is easy to see that t-immersion-critical graphs are 2-vertex-connected [1]. We now establish that they must in fact be at least 4-vertex-connected. Our work linking coloring to the immersion order begins in earnest with Lemma 4. First, however, we present something of an introduction with three easy but useful lemmas about cutsets, paths and coloring. Lemmas 1 and 2 are probably well known, although they may not be formulated anywhere else in precisely the same way we state them in this treatment. Lemma 2, which we dub *The Patching Lemma*, is especially helpful. Lemma 3 is certainly well known, and mentioned in a variety of sources (see, for example, [12, 25, 27]).

Lemma 1. *Let S denote a minimum-cardinality vertex cutset in a 2-vertex-connected graph G, and let C denote a connected component of $G\backslash S$. Then any two elements of S must be connected by a path whose interior vertices lie completely within C.*

Two colorings are said to be *equivalent* if the partitions induced by their respective color classes are identical.

Lemma 2. (The Patching Lemma) *Let S denote a vertex cutset of G, and let G_1 and G_2 denote a pair of induced subgraphs for which $G_1 \cup G_2 = G$ and $G_1 \cap G_2 = S$. If G_1 and G_2 admit t-colorings whose restrictions to S are equivalent, then G is t-colorable.*

The Patching Lemma can be used to establish the following well-known fact.

Lemma 3. *No vertex cutset of a t-color-critical graph can be a clique.*

The preceding lemmas tell us a good deal about the make-up of vertex cutsets, and how they relate to coloring. Armed with this information, we are now able to argue more directly about vertex connectivity and the immersion order. To simplify matters, we shall adopt the following conventions for the remainder of this subsection:

- t is at least five,
- G denotes a t-immersion-critical graph,
- S denotes a minimum-cardinality vertex cutset in G,
- C denotes a connected component of $G\backslash S$,
- G_1 denotes the subgraph induced by $C \cup S$, and
- G_2 denotes $G\backslash C$.

Lemma 4. *Every t-immersion-critical graph is 3-vertex-connected.*

Proof. Suppose otherwise, as witnessed by some G with $S = \{a, b\}$. We know from Lemma 3 that the edge ab is not present in G. Let $i \in \{1, 2\}$. By Lemma 1, there must be a path, P_i, with endpoints a and b, whose vertices lie completely within G_i. Lifting the edges of P_{3-i} to form the single edge ab, and then taking the subgraph induced by the vertices of G_i, produces a graph H_i properly immersed in G. It follows that H_i is $(t-1)$-colorable. Because ab is present in H_i, any such coloring of H_i assigns different colors to a and b. But G_i is a subgraph of H_i. Thus, there are $(t-1)$-colorings of G_1 and G_2 that each assign different colors to a and b. By the Patching Lemma, this ensures a $(t-1)$-coloring of G, a contradiction. □

Lemma 4 applies to t-topological-critical graphs as well. To see this, note that the two paths defined in the proof are vertex-disjoint. An analog of Lemma 4 does not hold, however, if the graph is only known to be t-color-critical. Such graphs are guaranteed only to be 2-vertex-connected. A t-color-critical graph that is not 3-vertex-connected can be constructed as follows. Begin with a pair of non-adjacent vertices, u and v, a copy of K_{t-1} and a copy of K_{t-2}. Connect u to every vertex but one in the copy of K_{t-1}. Connect v to the remaining vertex in the copy of K_{t-1}. Now connect both u and v to every vertex in the copy of K_{t-2}. Note that these graphs are not t-immersion-critical.

Lemma 5. *If $|S| = 3$, then G_1 and G_2 admit $(t-1)$-colorings that assign more than one color to the elements of S.*

Proof. Let $S = \{u, v, w\}$, and consider the case for G_1. By Lemma 1, there is a path between u and v in G_2. Lifting this path and taking the subgraph induced by the vertices of G_1 produces a graph H properly immersed in G. Because G is t-immersion-critical, and because H contains the edge uv, H must admit a $(t-1)$-coloring that assigns different colors to u and v. As a subgraph of H, G_1 can likewise be colored. A symmetrical argument handles the case for G_2. □

What we have really just shown is that if G is only 3-vertex-connected, then G_1 admits a $(t-1)$-coloring that assigns different colors to any fixed pair of elements of S. This raises the possibility that a single coloring of G_1 may suffice, simultaneously assigning different colors to all three elements of S. We now show that this cannot happen. It follows that the same must then be true for G_2.

Let a and b denote vertices of G, and let c denote a coloring of G in which $c(a) = i \neq j = c(b)$. If a and b belong to the same connected component of c_{ij}, then they are connected by some Kempe chain P_{ij} contained within c_{ij}. In this event, we say that a and b are *c-chained*.

Lemma 6. *If $|S| = 3$, then neither G_1 nor G_2 admits a $(t-1)$-coloring that assigns three different colors to the elements of S.*

Proof Sketch. Suppose otherwise, as witnessed by a $(t-1)$-coloring c of G_1. Let $S = \{u, v, w\}$ and assume, without loss of generality, that $c(u) = 1, c(v) = 2$ and $c(w) = 3$. Let d denote some $(t-1)$-coloring of G_2. By Lemma 5 and the Patching Lemma, it must be that d assigns exactly two colors to the elements of S. So assume, again without loss of generality, that $d(u) = d(v)$. If u and v are not c-chained, then we can exchange colors 1 and 2 in $c_{12}(v)$ to produce a $(t-1)$-coloring c' of G_1 that assigns color 1 to both u and v and leaves the color of w set to 3. This means that the restrictions of c' and d to S are equivalent. But now, by the Patching Lemma, G is $(t-1)$-colorable, which is impossible. Thus it must be that u and v are c-chained by some P_{12} in G_1. The proof proceeds by identifying P_{13} and P_{23} in a similar fashion. These chains are lifted simultaneously, along with one more application of the Patching Lemma. □

Bolstered by the preceding Lemmas, we are now ready to prove that minimum-cardinality vertex cutsets of t-immersion-critical graphs have at least four elements. The use of Kempe chains in Lemma 6 has been especially effective, so much so that we need only paths not chains in what follows.

Theorem 2. *Every t-immersion-critical graph is 4-vertex-connected.*

Proof. Suppose otherwise, as witnessed by some G with $S = \{u, v, w\}$. Let c and d denote $(t-1)$-colorings of G_1 and G_2, respectively. By Lemmas 5 and 6, we restrict our attention to the case in which both c and d assign exactly two colors to elements of S. Without loss of generality, assume $c(u) = c(v)$ and $d(u) = d(w)$. By Lemma 1, there is a path P_1 in G_1 whose endpoints are u and w. Similarly, there is a path P_2 in G_2 whose endpoints are u and v. Lifting P_i and taking the graph induced by the vertices of G_{3-i} produces a graph H_{3-i} properly immersed in G. H_1 contains uv, and so must admit a $(t-1)$-coloring c' that assigns different colors to u and v. G_1 is likewise colored by c'. By Lemma 6, c' cannot assign a third color to w. Lest the restrictions of c' and d to S be equivalent, it must be that $c'(w) = c'(v)$. H_2 contains uw, and so must admit a $(t-1)$-coloring d' that assigns different colors to u and w. G_2 is likewise colored by d'. By Lemma 6, d' cannot assign a third color to v. But if $d'(v) = d'(u)$, then the restrictions of c and d' to S are equivalent. And if $d'(v) = d'(w)$, then the restrictions of c' and d' to S are equivalent. Thus, under some pair of colorings of G_1 and G_2, the Patching Lemma ensures that G is $(t-1)$-colorable, a contradiction. □

3.2 Edge Connectivity

Because the immersion order includes the taking of subgraphs, we know that t-immersion-critical graphs are also t-color-critical. From the work of [24] it follows that they are $(t-1)$-edge-connected. We now show that any t-immersion-critical graph other than K_t is in fact t-edge-connected. We begin a pair of well-known observations (see, for example, [27]).

Observation 4. *A minimum-cardinality edge cutset separates a graph into exactly two connected components.*

Observation 5. *If H is obtained by deleting the edge uv from a t-color-critical graph, then H is $(t-1)$-colorable and, under any $(t-1)$-coloring, u and v are assigned the same color.*

The significance of Observation 5 rests with the next lemma, which plays an essential role in our edge-connectivity arguments. This lemma is probably also well known, although it may not be formulated elsewhere in exactly the same way we state it here.

Lemma 7. *Let H be obtained by deleting the edge uv from a t-color-critical graph. Let c denote a $(t-1)$-coloring of H with $c(u) = c(v) = 1$. Then $v \in c_{1i}(u) \forall i \in \{2, 3, \ldots, t-1\}$.*

Proof. Let H and c be defined as stated. Suppose the lemma is false, as witnessed by some i with $v \notin c_{1i}(u)$. Exchanging colors 1 and i in $c_{1i}(u)$ produces c', another $(t-1)$-coloring of H. But then u and v are assigned different colors under c', which is impossible. □

Aided by this information about color-criticality, we are now able to argue more directly about edge connectivity and the immersion order. We shall adopt the following conventions for the remainder of this subsection:

- t is at least 5,
- G denotes a t-immersion-critical graph,
- S denotes a minimum-cardinality edge cutset in G,
- C_1 and C_2 denote the two connected components of $G \backslash S$,
- S_1 and S_2 denote the endpoints of S contained in C_1 and C_2, respectively,
- uv denotes an element of S, with $u \in S_1$ and $v \in S_2$, and
- H denotes $G \backslash \{uv\}$.

Lemma 8. *If G is not t-edge-connected, then every $(t-1)$-coloring of H assigns either one color to S_1 and all $t-1$ colors to S_2 or vice versa.*

Proof Sketch. Suppose G is not t-edge-connected. We know from [24] that S has cardinality $t-1$. Let c denote a $(t-1)$-coloring of H with $c(u) = c(v) = 1$. Lemma 7 ensures that $v \in c_{1i}(u) \forall i \in \{2, 3, .., t-1\}$. Therefore u and v are the endpoints of $t-2$ Kempe chains, where each chain is contained within $c_{1i}(u)$ for some i. By Observation 1, the chains are edge disjoint, and so each contains at least one distinct element of $S' = S \backslash \{uv\}$. Thus there is a one-to-one correspondence between chains and elements of S'. This means that every element of S' has an endpoint assigned color 1 by c. If c assigns only color 1 to S_1, then it must assign all $t-1$ colors to S_2. Similarly, if c assigns all $t-1$ colors to S_1, then it must assign only color 1 to S_2. The only remaining case occurs if c assigns more than one but fewer than $t-1$ colors to S_1. This is handled with a contradiction-based argument and an application of Lemma 7. □

Theorem 3. *Any t-immersion-critical graph other than K_t is t-edge-connected.*

Proof Sketch. Suppose otherwise, as witnessed by some G, not isomorphic to K_t, that is only $(t-1)$-edge-connected. We apply Lemma 8 and, without loss of generality, let c denote a $(t-1)$-coloring of H that assigns color 1 to $S_1 \cup \{v\}$.

Thus all $t-1$ colors are assigned to S_2. From here Kempe chains are applied to show that K_{t-1} is immersed in C_2 using a model whose corners are the elements of S_2. With another application of Lemma 8, a K_t is found to be immersed in G using a model whose corners are $u \cup S_2$. □

Corollary 1. *If G is t-immersion-critical and not K_t, then $\delta(G) \geq t$.*

Proof. Immediate from Theorem 3 and the fact that $\delta(G)$ is an upper bound on G's edge connectivity. □

Corollary 2. *If G is t-color-critical with a vertex u of degree $t-1$, then K_t is immersed in G via a model whose corners are $u \cup N(u)$.*

Proof. Follows from the proof of Theorem 3 by letting S be the set of edges incident on u. □

4 Conclusions

We note that previous work on Hajós conjecture provides additional supporting evidence for both the $t = 5$ and $t = 6$ cases. If our conjecture is true in these cases, then it has no effect on Hajós conjecture. This is because a t-chromatic graph may contain an immersed K_t with or without containing a topological K_t. On the other hand, if our conjecture is false for either case, then it means that Hajós conjecture is also false for that case. This is because a t-chromatic graph without an immersed K_t must also be without a topological K_t. This would be quite a revelation, given that Hajós conjecture for $t \in \{5, 6\}$ has remained open for roughly 60 years.

Settling the general case seems rather foreboding. Perhaps this view is unfairly influenced, however, by knowledge of the long-standing difficulty of settling Hadwiger's conjecture. Observe that Kempe chains are not vertex disjoint. Yet the minor order is inherently dependent on vertex-disjoint paths. In this we sense room for optimism: the immersion order is concerned only with edge-disjoint paths, and Kempe chains are indeed edge disjoint. Given the vast array of applications for coloring and the immersion order, we believe that the nature of their relationship warrants continued study.

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