Completeness in the Boolean Hierarchy: Exact-Four-Colorability, Minimal Graph Uncolorability, and Exact Domatic Number Problems

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Abstract

This paper surveys some of the work that was inspired by Wagner’s general technique to prove completeness in the levels of the boolean hierarchy over NP and some related results. In particular, we show that it is DP-complete to decide whether or not a given graph can be colored with exactly four colors, where DP is the second level of the boolean hierarchy. This result solves a question raised by Wagner in 1987, and its proof uses a clever reduction due to Guruswami and Khanna. Another result covered is due to Cai and Meyer: The graph minimal uncolorability problem is also DP-complete. Finally, similar results on various versions of the exact domatic number problem are discussed.

Key words: Boolean hierarchy, completeness, exact colorability, exact domatic number, minimal uncolorability.

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1 Introduction, Historical Notes, and Definitions

This paper surveys completeness results in the levels of the boolean hierarchy over NP, with a special focus on Wagner’s work [Wag87]. His general technique for proving completeness in the boolean hierarchy levels—as well as in other classes such as \( P_{||}^{NP} \), the class of problems solvable via parallel access to NP—inspired much of the recent results in this area. Quoting Papadimitriou, the boolean hierarchy is “somewhat sparse in natural complete sets” (see p. 434 of [Pap95]). This statement certainly is true—in particular, if the number of natural problems complete in higher boolean hierarchy levels is set off against the number of natural NP-complete problems. However, even the higher levels of the boolean hierarchy do contain very natural, beautiful complete problems, and since there are only few of them known, we should seek to find more. This line of research has been intensely pursued since the late 1980s, and much work has been done in a number of recent papers. The purpose of the present survey is to give an overview of this progress of results.

But first, let us look back a bit further and start with the beginning. In the 1970s, Meyer and Stockmeyer [MS72, Sto77] noted that the minimum equivalent expression problem for boolean formulas in disjunctive normal form (DNF, for short), which is defined by

\[
\text{MEE-DNF} = \left\{ \langle \varphi, k \rangle \mid \varphi \text{ is a boolean formula in DNF, } k \geq 0, \text{ and there exists a boolean formula } \psi \text{ with at most } k \text{ literals such that } \psi \text{ is equivalent to } \varphi \right\},
\]

is coNP-hard but seems to be not coNP-complete. Motivated by this observation, they introduced the polynomial hierarchy in order to capture the complexity of problems that appear to be beyond NP and coNP.

Definition 1 (Polynomial Hierarchy) The polynomial hierarchy is inductively defined by:

- \( \Delta^p_0 = \Sigma^p_0 = \Pi^p_0 = \text{P} \),
- for \( i \geq 0 \), \( \Delta^p_{i+1} = \text{P}^{\Sigma^p_i} \), \( \Sigma^p_{i+1} = \text{NP}^{\Sigma^p_i} \), and \( \Pi^p_{i+1} = \text{coNP}^{\Sigma^p_i} \), and
- \( \text{PH} = \bigcup_{k \geq 0} \Sigma^p_k \).

Meyer and Stockmeyer observed that \( \text{MEE-DNF} \) is contained in \( \Sigma^p_2 = \text{NP}^{\text{NP}} \), but left open the question of whether or not it is \( \Sigma^p_2 \)-complete.

In this paper, all hardness and completeness results are with respect to the polynomial-time many-one reducibility, denoted by \( \leq^p_m \). For sets \( A \) and \( B \), we write \( A \leq^p_m B \) if and only if there is a polynomial-time computable function \( f \) such that for each \( x \in \Sigma^*, x \in A \) if and only if \( f(x) \in B \). A set \( B \) is said to be \( C \)-hard for a complexity class \( C \) if and only if \( A \leq^p_m B \) for each \( A \in C \). A set \( B \) is said to be \( C \)-complete if and only if \( B \) is \( C \)-hard and \( B \in C \).

Figure 1 shows the inclusion structure of the polynomial hierarchy.

Papadimitriou and Zachos [PZ83] introduced \( P^{\text{NP}[O(\log n)]} \), the class of problems solvable by \( O(\log n) \) sequential Turing queries to NP. Köhler, Schöning, and Wagner [KSW87] and, independently, Hemaspaandra [Hem87] proved that \( P^{\text{NP}[O(\log n)]} \) equals \( P_{||}^{NP} \), the class of problems solvable by parallel (a.k.a. truth-table) access to NP. Wagner [Wag90] provided about half a dozen other characterizations of this class, and he introduced the notation \( \Theta^p_i \) for it. By definition, \( \text{NP} \subseteq \Theta^p_i \subseteq \Delta^p_i \). It is known that if NP contains some problem that is hard for \( \Theta^p_i \), then the polynomial hierarchy collapses to NP, see Meyer and Stockmeyer [MS72, Sto77]. The class \( \Theta^p_i \) is also closely related to the question of whether NP has sparse Turing-hard sets [Kad89], and to various other topics; see, e.g., [LS95, Kre88, HW91]. Wagner also introduced the classes \( \Theta^p_i = \text{P}^{\Sigma^p_{i-1}[O(\log)]} \) for each \( i \geq 1 \), as a straightforward generalization of \( \Theta^p_i \) to higher levels of the polynomial hierarchy.
In the 1980s, Papadimitriou and Yannakakis [PY84] noted that certain NP-hard and coNP-hard problems seem to be not complete for NP or coNP:

- **Exact problems** such as **Exact-4-Colorability**: Given a graph, is it true that it can be legally colored with **exactly** four colors? (See Definition 3 below.)
- **Critical Problems** such as **Minimal-3-Uncolorability**: Given a graph, is it true that it is not 3-colorable, yet deleting any of its vertices makes it 3-colorable? (See Definition 10 in Section 4.)
- **Unique solution problems** such as **Unique-SAT**: Given a boolean formula, is it true that it has **exactly** one satisfying assignment?

Motivated by this observation, they introduced the class of differences of NP sets:

\[ \text{DP} = \{ A - B \mid A, B \in \text{NP} \}. \]
All the above problems are in DP.

The complexity of colorability problems has been studied intensely, see, e.g., [AH77a, AH77b, Sto73, GJS76, Wag87, KV91, Rot00, GRW01a, GRW01b, Rot03].

**Definition 2 (Colorability Problem)** For any graph \( G \), \( \chi(G) \) is the chromatic number of \( G \), i.e., the smallest number of colors needed to legally color \( G \). For each \( k \), define

\[
k\text{-Colorability} = \{ G \mid G \text{ is a graph with } \chi(G) \leq k \}.
\]

The problem 2-Colorability is contained in P, yet 3-Colorability is NP-complete, see Stockmeyer [Sto73]. We now define the exact versions of colorability problems.

**Definition 3 (Exact Colorability Problems)** Let \( M_k \) be a set that consists of \( k \) noncontiguous integers, and let \( t \) be a positive integer. Define

\[
\text{Exact-M}_k\text{-Colorability} = \{ G \mid G \text{ is a graph with } \chi(G) \in M_k \},
\]

\[
\text{Exact-}t\text{-Colorability} = \{ G \mid G \text{ is a graph with } \chi(G) = t \}.
\]

Merging, unifying, and expanding the results that originally were obtained independently by Cai and Hemaspaandra [CH86] and by Gundermann, Wagner, and Wechsung [Wec85, GW87], Cai et al. [CGH+88, CGH+89] generalized DP by introducing the boolean hierarchy over NP. To define this hierarchy, we use the symbols \( \wedge \) and \( \lor \), respectively, to denote the complex intersection and the complex union of set classes:

\[
C \wedge D = \{ A \cap B \mid A \in C \text{ and } B \in D \};
\]

\[
C \lor D = \{ A \cup B \mid A \in C \text{ and } B \in D \}.
\]

**Definition 4 (Boolean Hierarchy over NP)** The boolean hierarchy over NP is inductively defined by:

\[
\begin{align*}
\text{BH}_0(\text{NP}) & = P, \quad \text{BH}_1(\text{NP}) = \text{NP}, \quad \text{BH}_2(\text{NP}) = \text{NP} \wedge \text{coNP} = \text{DP}, \\
\text{BH}_k(\text{NP}) & = \text{BH}_{k-2}(\text{NP}) \lor \text{BH}_2(\text{NP}) \quad \text{for } k \geq 3, \text{ and} \\
\text{BH}(\text{NP}) & = \bigcup_{k \geq 1} \text{BH}_k(\text{NP}).
\end{align*}
\]

Figure 2 illustrates the inclusion structure of the boolean hierarchy over NP. Note further that it is \( \text{BH}(\text{NP}) \subseteq \Theta^p_2 \subseteq \Delta^p_2 \subseteq \Sigma^p_2 \subseteq \text{PH} \). Kadin [Kad88] was the first to show that a collapse of the boolean hierarchy implies a collapse of the polynomial hierarchy.

**Theorem 5 (Kadin)** If \( \text{BH}_k(\text{NP}) = \text{coBH}_k(\text{NP}) \) for some \( k \geq 1 \), then the polynomial hierarchy collapses down to its third level: \( \text{PH} = \Sigma^p_3 \cap \Pi^p_3 \).

The collapse consequence of Theorem 5 has been strengthened later on; see the survey by Hemaspaandra, Hemaspaandra, and Hempel [HHH98].

### 2 Some Results Obtained by Wagner’s Technique

Wagner [Wag87] established conditions sufficient to prove hardness for \( \Theta^p_2 \) and for the levels of the boolean hierarchy over NP. We first state his sufficient condition for proving \( \Theta^p_2 \)-hardness.
\[ \Theta_2^P = \text{P}^{\text{NP}[O(\log)]} \]
\[ \text{BH}(\text{NP}) = \text{P}^{\text{NP}[O(1)]} \]
\[ \text{coBH}_3(\text{NP}) \]
\[ \text{BH}_3(\text{NP}) \]
\[ \text{coDP} = \text{coBH}_2(\text{NP}) \]
\[ \text{BH}_2(\text{NP}) = \text{DP} \]
\[ \text{coNP} = \text{coBH}_1(\text{NP}) \]
\[ \text{BH}_1(\text{NP}) = \text{NP} \]
\[ P = \text{BH}_0(\text{NP}) \]

Figure 2: The boolean hierarchy over \( \text{NP} \)

**Lemma 6 (Wagner)** Let \( A \) be some \( \text{NP} \)-complete set, and let \( B \) be any set. If for all \( \varphi_1, \ldots, \varphi_k \) in \( \Sigma^* \) with \( (\forall j : 1 \leq j < k) [\varphi_{j+1} \in A \implies \varphi_j \in A] \) there exists a polynomial-time computable function \( g \) such that
\[ ||\{i \mid \varphi_i \in A\}|| \text{ is odd} \iff g(\varphi_1, \ldots, \varphi_k) \in B, \] then \( B \) is \( \Theta_2^P \)-hard.

Using Lemma 6, Wagner proved dozens of problems \( \Theta_2^P \)-complete, including the following variants of the colorability problem:

- **Color_{odd}** = \( \{G \mid G \text{ is a graph such that } \chi(G) \text{ is odd}\} \)
- **Color_{equ}** = \( \{(G, H) \mid G \text{ and } H \text{ are graphs with } \chi(G) = \chi(H)\} \)
- **Color_{leq}** = \( \{(G, H) \mid G \text{ and } H \text{ are graphs with } \chi(G) \leq \chi(H)\} \)

Wagner’s technique has been applied to prove further natural problems, which arise in a variety of contexts, \( \Theta_2^P \)-hard or even \( \Theta_2^P \)-complete. For example, Lemma 6 was useful in determining the complexity of the winner problem for certain voting systems, including Carroll elections [HHR97a], Young elections [RSV03], and Kemeny elections [HSV05]. For more background on computational politics, see Hemaspaandra and Hemaspaandra’s excellent survey [HH00] and, e.g., [BTT89a, BTT89b, BTT92, CS02a, CS02b, CLS03, HHR05].

Wagner’s technique was also useful for showing that recognizing those graphs for which certain efficient approximation heuristics for the independent set and the vertex cover problem do well is \( \Theta_2^P \)-complete [HR98, HRS06]; see also the survey [HHR97b]. Moreover, Lemma 6 is the key lemma for raising the trivial coNP-hardness of \( \text{MEE-DNF} \) to \( \Theta_2^P \)-hardness, see Hemaspaandra and Wechsung [HW02].

\(^1\)Note that Umans [Uma98] proved this problem even \( \Sigma_2^P \)-complete using a different technique. On the other hand, if the restriction to DNF formulas in the definition of \( \text{MEE-DNF} \) is being dropped, one obtains the problem \( \text{MEE} \), which
In what follows, we focus on completeness for exact colorability, minimal uncolorability, and exact domatic number problems in the even levels of the boolean hierarchy. The following lemma, which is also due to Wagner [Wag87], is the key lemma to establish most of these results.

**Lemma 7 (Wagner)**  Let $A$ be some $\text{NP}$-complete set, let $B$ be any set, and let $k \geq 1$ be fixed. If there exists a polynomial-time computable function $g$ such that for all $\varphi_1, \ldots, \varphi_{2^k}$ in $\Sigma^*$ with $(\forall j : 1 \leq j < 2^k) [\varphi_{j+1} \in A \implies \varphi_j \in A]$ it holds that

$$||\{i \mid \varphi_i \in A\}|| \text{ is odd } \iff g(\varphi_1, \ldots, \varphi_{2^k}) \in B,$$

then $B$ is $\text{BH}_{2^k}(\text{NP})$-hard.

### 3 Exact Colorability Problems

In this section, we turn to the exact colorability problems defined in Definition 3. Using Lemma 7, Wagner [Wag87] proved the following result.

**Theorem 8 (Wagner)**  The problem $\text{Exact-}M_k\text{-Colorability}$ is $\text{BH}_{2^k}(\text{NP})$-complete for the set $M_k = \{6k + 1, 6k + 3, \ldots, 8k - 1\}$. In particular, for $k = 1$, it is $\text{DP}$-complete to determine whether or not $\chi(G) = 7$.

Wagner [Wag87] raised the following questions: How small can the numbers in a $k$-element set $M_k$ be chosen so as to ensure that $\text{Exact-}M_k\text{-Colorability}$ still is $\text{BH}_{2^k}(\text{NP})$-complete? In particular, for $k = 1$, is it $\text{DP}$-complete to determine whether or not $\chi(G) = 4$? That is, for which threshold $t \in \{4, 5, 6, 7\}$ exactly does $\text{Exact-}t\text{-Colorability}$ jump from $\text{NP}$ to $\text{DP}$-complete?

These questions have been answered recently, see Rothe [Rot03]. Note that $\text{Exact-3-Colorability}$ is in $\text{NP}$ and thus cannot be $\text{DP}$-complete, unless the boolean hierarchy over $\text{NP}$ (and, by Theorem 5, the polynomial hierarchy as well) collapses.

**Theorem 9 (Rothe)**  The problem $\text{Exact-}M_k\text{-Colorability}$ is $\text{BH}_{2^k}(\text{NP})$-complete for the set $M_k = \{3k + 1, 3k + 3, \ldots, 5k - 1\}$. In particular, for $k = 1$, it is $\text{DP}$-complete to determine whether or not $\chi(G) = 4$.

A proof sketch for Theorem 9 is presented in the remainder of this section. Crucially, this proof uses:

- Wagner’s tool for proving $\text{BH}_{2^k}(\text{NP})$-hardness stated as Lemma 7 above,

- the standard reduction $f$ from $3\text{-SAT}$ to $3\text{-Colorability}$ satisfying

$$\varphi \in 3\text{-SAT} \implies \chi(f(\varphi)) = 3,$$  \quad (3.3)

$$\varphi \not\in 3\text{-SAT} \implies \chi(f(\varphi)) = 4,$$  \quad (3.4)

- and Guruswami and Khanna’s reduction $g$ from $3\text{-SAT}$ to $3\text{-Colorability}$ satisfying

$$\varphi \in 3\text{-SAT} \implies \chi(g(\varphi)) = 3,$$  \quad (3.5)

$$\varphi \not\in 3\text{-SAT} \implies \chi(g(\varphi)) = 5.$$  \quad (3.6)

Trivially is in $\Sigma^p_2$ and which is known to be $\Theta^p_2$-hard by Hemaspaandra and Wechsung’s result [HW97]. The precise complexity of $\text{MEE}$ is still unknown.
Among the above three items, the Guruswami–Khanna reduction is the technically most challenging one. Originally, Guruswami and Khanna’s seminal result is not motivated by the issue of proving the hardness of exact colorability. Rather, it was motivated by issues related to the hardness of approximating the chromatic number of 3-colorable graphs. Intuitively, their result says that it is NP-hard to 4-color a 3-colorable graph. This result had been obtained earlier on by Khanna, Linial, and Safra [KLS00] using the PCP theorem, which is due to Arora, Lund, Motwani, Sudan, and Szegedy [ALM+98]. Guruswami and Khanna [GK00] gave a novel proof of this result, which does not rely on the PCP theorem. Their direct transformation in fact consists of the following two subsequent reductions:

\[ 3\text{-SAT} \leq^p_m \text{IS} \leq^p_m 3\text{-Colorability}, \]

where IS is the independent set problem: Given a graph \( G \) and a positive integer \( k \), does \( G \) have an independent set of size at least \( k \), i.e., a subset \( I \) of \( G \)'s vertex set with \( |I| \geq k \) such that there is no edge between any pair of vertices in \( I \).

Figure 3 shows the standard reduction \( 3\text{-SAT} \leq^p_m \text{IS} \), for the specific formula

\[ \varphi(x, y, z) = (x \lor y \lor z) \land (\neg x \lor \neg y \lor z) \land (x \lor y \lor \neg z) \land (x \lor \neg y \lor z). \]

Clauses in the formula correspond to triangles in the graph constructed, and corners of two distinct triangles are connected by an edge if and only if they correspond to some literal and its negation. Suppose the given formula has \( m \) clauses, and denote the corresponding \( m \) triangles in \( G \) by \( T_1, T_2, \ldots, T_m \). To each \( T_i \) in \( G \), there corresponds a tree-like structure \( S_i \) as shown in Figure 4:

Figure 4: Tree-like structure \( S_i \) in the Guruswami–Khanna reduction

The three “leaves” \( t_{i,1}, t_{i,2}, \) and \( t_{i,3} \) in \( S_i \) correspond to the three corners of the triangle \( T_i \). Every “vertex” of \( S_i \) has the form of the basic template, which is a \( 3 \times 3 \) grid such that the vertices in each row and column induce a 3-clique as shown in Figure 5: The “ground vertices” in the first column of any such basic template in fact are shared among all basic templates in each of the tree-like
structures. Since these ground vertices form a 3-clique, every legal coloring assigns three distinct colors to them, say 1, 2, and 3.

Figure 6 shows the connection pattern between the “vertices” \( r_i, t_{i,1}, \) and \( s_i \) of \( S_i \) and two additional triangles. An analogous pattern applies to \( s_i, t_{i,2}, \) and \( t_{i,3} \). Every vertex of the templates and the triangles is labeled by a triple of colors, and the vertices are connected according to the following simple rule: Two vertices are adjacent if and only if their labels differ in each coordinate.

A “vertex” in some \( S_i \) is said to be selected (with respect to some coloring) if and only if at least one of the three rows in its basic template receives colors that form an even permutation of \{1, 2, 3\}. That is, a “vertex” is selected if and only if

- the first row has colors 1, 2, 3 from left to right, or
- the second row has colors 2, 3, 1 from left to right, or
- the third row has colors 3, 1, 2 from left to right.

Clearly, for each legal 4-coloring of \( S_i \), every “vertex” is either selected or not selected. Adding three more edges to each “vertex” \( r_i \), the selection of every \( 3 \times 3 \) root grid is enforced, as is shown in Figure 7. From the way the grids are connected, it follows that for any legal 4-coloring, selection of an internal “vertex” is propagated to at least one of its children. Therefore at least one of the “leaves” \( t_{i,1}, t_{i,2}, \) and \( t_{i,3} \) must be selected as well. Additionally, it can be shown that for each
“leaf” $t_{i,j}$, $1 \leq j \leq 3$, in a tree-structure $S_i$, there exists a legal 3-coloring of the vertices of $S_i$, where $t_{i,j}$ is the only “leaf” selected; see Properties (a) and (b) stated below.

![Figure 7: The root grid altered such that selection is enforced](image)

The intuition of how to connect $S_i$ and $S_j$, for distinct $i$ and $j$, is as follows. For each pair of “vertices,” $t_{i,k}$ and $t_{j,\ell}$, that are adjacent in graph $G$, appropriate gadgets are inserted to prevent that both these “leaves” are selected simultaneously. (This is necessary, since otherwise any 4-coloring of the graph constructed would imply that $G$ has an independent set of size $m$.)

![Figure 8: Gadget connecting two “leaves” of the same row kind](image)

To this end, two kinds of gadgets are used, the “same row” gadget and the “different rows” gadget. Figure 8 shows the same row gadget, which prevents that $t_{i,k}$ and $t_{j,\ell}$ are simultaneously selected because of the same row. Figure 9 shows the different rows gadget, which prevents that $t_{i,k}$ and $t_{j,\ell}$ are selected simultaneously because of different rows.

This completes the reduction $g$ that transforms the formula $\varphi$ via graph $G$ to graph $H = g(\varphi)$. We omit the detailed argument of why this reduction works to prove (3.5) and (3.6), referring to Guruswami and Khanna [GK00] instead. We merely mention that it can be shown that:

(a) For each $i$ with $1 \leq i \leq m$, there exists a legal 3-coloring of the vertices in $S_i$ such that exactly one of the three “leaves” $t_{i,1}$, $t_{i,2}$, and $t_{i,3}$ is selected.

(b) Every legal 4-coloring of $S_i$ selects at least one of $t_{i,1}$, $t_{i,2}$, or $t_{i,3}$.

The implications (3.5) and (3.6) follow from (a) and (b).

Note that Guruswami and Khanna claimed in their conference paper [GK00] that $\varphi \not\in 3{-\text{SAT}}$ implies $5 \leq \chi(H) \leq 6$. However, as has been observed in [Rot03], the Guruswami–Khanna reduction even yields the stronger implication (3.6), which is needed in order to apply Wagner’s Lemma 7.
Figure 9: Gadget connecting two “leaves” of the different rows kind

Setting $A = 3$-SAT, $B = \text{Exact-4-Colorability}$ and $k = 1$, we are now ready to apply Lemma 7. Given two formulas $\varphi_1$ and $\varphi_2$ satisfying

$$\varphi_2 \in 3\text{-SAT} \implies \varphi_1 \in 3\text{-SAT},$$

(3.7)

define the graphs $H_1 = g(\varphi_1)$ and $H_2 = f(\varphi_2)$, where $g$ is the Guruswami–Khanna reduction, which satisfies (3.5) and (3.6), and $f$ is the standard reduction from 3-SAT to 3-Colorability, which satisfies (3.3) and (3.4).

Let $D$ be the disjoint union of $H_1$ and $H_2$. Thus,

$$\chi(D) = \max\{\chi(H_1), \chi(H_2)\}.$$

Consider the following three cases:

- If $\varphi_1 \in 3\text{-SAT}$ and $\varphi_2 \in 3\text{-SAT}$, then $\chi(\varphi_1) = 3$ and $\chi(\varphi_2) = 3$, so $\chi(D) = 3$.
- If $\varphi_1 \in 3\text{-SAT}$ and $\varphi_2 \notin 3\text{-SAT}$, then $\chi(\varphi_1) = 3$ and $\chi(\varphi_2) = 4$, so $\chi(D) = 4$.
- If $\varphi_1 \notin 3\text{-SAT}$ and $\varphi_2 \notin 3\text{-SAT}$, then $\chi(\varphi_1) = 5$ and $\chi(\varphi_2) = 4$, so $\chi(D) = 5$.

By (3.7), the case distinction is complete. It follows that (2.2) is satisfied. By Lemma 7, it holds that Exact-4-Colorability is DP-hard. Since Exact-4-Colorability is in DP, it is DP-complete. For the $k$-element set $M_k = \{3k + 1, 3k + 3, \ldots, 5k - 1\}$, completeness of Exact-$M_k$-Colorability in BH$_{2k}(NP)$ is proven analogously.

4 The Graph Minimal Uncolorability Problem

This section presents a well-known and typical example of a critical graph problem. A graph $G$ is said to be critical if and only if by deleting any one of the vertices of $G$ (respectively, by adding one vertex to $G$), the graph gains a certain property that it did not have before the removal (respectively, before the insertion) of this vertex. Similarly, one can define critical graph problems with respect to adding or removing edges in such a way that a specific property of the graph is triggered. Critical problems\footnote{Needless to say that the class of critical problems is not restricted to graph problems but can be defined in a broader sense. Here, however, we focus on some particularly interesting critical graph problem.} are good candidates for DP-completeness; usually, these problems are easily shown to be contained in DP. The first example of a critical problem is given below.
Definition 10 (Graph Minimal Uncolorability) Minimal-k-Uncolorability is a critical graph problem defined as follows: Given a graph $G$ with vertex set $V(G)$ and edge set $E(G)$, is it true that if $G \notin k$-Colorability, but for every vertex $v \in V(G)$ it holds that $G - \{v\}$ is in the set $k$-Colorability? Here, $G - \{v\}$ denotes the induced subgraph that is obtained from $G$ by deleting vertex $v$ from $V(G)$ and all incident edges from $E(G)$.

We are interested in the particular problem Minimal-3-Uncolorability, and we use $\text{M-3-UC}$ as a shorthand for this problem. The following theorem is due to Cai and Meyer [CM87]. To prove DP-hardness of $\text{M-3-UC}$, they give a reduction from the problem Minimal-3-UNSAT, which was shown to be DP-complete by Papadimitriou and Wolfe [PW88]. The Minimal-3-UNSAT problem asks, given a boolean formula $\varphi$ whose clauses contain exactly three literals each, is it true that $\varphi$ is not satisfiable, but removing any one of its clauses makes $\varphi$ satisfiable?

Theorem 11 (Cai and Meyer) The problem $\text{M-3-UC}$ is DP-complete.

To see that $\text{M-3-UC}$ is in DP, consider the two sets
\[
A = \{G \mid G \text{ is a graph with } \chi(G - \{v\}) \leq 3 \text{ for all vertices } v \in V(G)\} \quad \text{and} \\
B = \{G \mid G \text{ is a graph with } \chi(G) > 3\}.
\]

Note that $A$ is in NP, $B$ is in coNP, and $\text{M-3-UC} = A \cap B$. The remainder of this section deals with the reduction from Minimal-3-UNSAT to $\text{M-3-UC}$, which preserves the critical property of the problem instance and thus proves DP-hardness of $\text{M-3-UC}$.

Let the boolean formula $\varphi = (X, C)$ with variable set $X = \{x_1, x_2, \ldots, x_n\}$ and clause set $C = \{c_1, c_2, \ldots, c_m\}$ be given. Define the reduction $f$ that maps $\varphi$ to a graph $G$ as follows. First, create two distinct vertices, $v_c$ and $v_s$, and an edge connecting them. For each variable $x_i$, add the two vertices $x_i$ and $\neg x_i$, representing its literals to $G$, and insert edges such that every pair of literal vertices corresponding to the same variable forms a triangle with the vertex $v_c$.

Suppose there exists a legal 3-coloring of $G$, and let $\{T, F, C\}$ be the color set. Without loss of generality, let $v_c$ be colored with $C$, and let $v_s$ be colored with $T$. Then, only the colors $T$ and $F$ are available for any pair of literal vertices $x_i$ and $\neg x_i$, see Figure 10. Thus, a legal 3-coloring of $G$ may be regarded as a truth assignment of the variables of $\varphi$.

![Figure 10: A legal 3-coloring of $v_c$, $v_s$, and the literal vertices of graph $G$](image)

Finally, components for the clauses of $\varphi$ are inserted. If $c_j = (\ell_j^1 \vee \ell_j^2 \vee \ell_j^3)$ is any clause of $C$, create a triangle with vertices $t_j^1$, $t_j^2$, and $t_j^3$. Additionally, for each literal $\ell_{jk}$ with $1 \leq k \leq 3$ in $c_j$, there are two vertices, $a_{jk}$ and $b_{jk}$, such that $a_{jk}$ is adjacent to the corresponding literal vertex $\ell_{jk}$,
and $b_{jk}$ is adjacent to the triangle vertex $t_{jk}$. Figure 11 shows some legally colored component for the specific clause $c_1 = (\neg x_1 \lor x_2 \lor \neg x_3)$.

![Figure 11: A legal 3-coloring of the clause component for $c_1 = (\neg x_1 \lor x_2 \lor \neg x_3)$](image)

Note that the triangle with the vertices $t_{j1}$, $t_{j2}$, and $t_{j3}$ for some clause $c_j$ is legally 3-colorable if and only if not all of the so-called “fanout” vertices $b_{j1}$, $b_{j2}$, and $b_{j3}$ are assigned color F. Coloring one of the fanout vertices of some clause $c_j$ with C is possible only if the literal vertices are colored according to some truth assignment that satisfies the clause $c_j$.

This completes the reduction $f$ mapping the boolean formula $\varphi$ to the graph $G = f(\varphi)$. Figure 12 shows the graph $G = f(\varphi)$ resulting from the specific formula

$$
\varphi(x_1, x_2, x_3) = (x_1 \lor x_2 \lor x_3) \land (\neg x_2 \lor x_3 \lor \neg x_4).
$$

It can be shown that $\varphi$ is satisfiable if and only if $G = f(\varphi)$ can be legally 3-colored. The proof is similar to the one proving NP-hardness for 3-Colorability via the standard reduction from 3-SAT; see, e.g., Stockmeyer, Garey, and Johnson [Sto73, GJS76, GJ79]. It remains to prove that

$$
\varphi \in \text{Minimal-3-UNSAT} \iff G \in \text{Minimal-3-Uncolorability}.
$$

For the direction from left to right, it is known from the claim above that the reduction $f$ will transform any unsatisfiable formula $\varphi$ into a graph $G$ that does not have a legal 3-coloring. Analyzing the various possibilities of removing a vertex from $G$ (for example, some literal vertex $x_i$ or $\neg x_i$), a legal 3-coloring for the graph $G - \{v\}$ has to be determined.

For the direction from right to left, note that $G \notin \text{3-Colorability}$ implies $\varphi \notin \text{3-SAT}$. Removing a clause $c_j$ from $\varphi$, the satisfiability of the resulting formula can be deduced from the 3-colorable graph $G - \{t_{j1}\}$. For the details of the proofs of the two claims above, we refer to the original paper by Cai and Meyer [CM87].

The DP-completeness of Minimal-3-Uncolorability for $k = 3$ can easily be extended to all values of $k \geq 3$. Notice that Minimal-2-Uncolorability is in P, and thus cannot be DP-complete unless the boolean hierarchy collapses. Cai and Meyer also showed DP-completeness of the critical problem Minimal-3-Uncolorability when the input is restricted to planar graphs, or to graphs with a maximum degree of five.
5 Exact Domatic Number Problems

The domatic number problem is the problem of partitioning the vertex set $V(G)$ into a maximum number of disjoint dominating sets. This number, denoted by $\delta(G)$, is called the domatic number of $G$. The domatic number problem arises in various real-world scenarios. For example, it is related to the tasks of distributing resources in a computer network or of locating facilities in a communication network; see, e.g., [FHK00, RR04a] for details. The domatic number problem and the closely related problem of finding a minimum dominating set in a given graph have been thoroughly studied. To name just a few papers, see, e.g., [CH77, Far84, Bon85, KS94, HT98, FHK00, RR04a, RR05, RRSY06].

Definition 12 (Domatic Number Problem) For any graph $G$, a dominating set of $G$ is a subset $D \subseteq V(G)$ such that each vertex $u \in V(G) - D$ is adjacent to some vertex $v \in D$. Let $\delta(G)$ denote the domatic number of $G$, i.e., the maximum number of disjoint dominating sets. For each $k$, define the problem

$$k\text{-DNP} = \{G \mid G \text{ is a graph with } \delta(G) \geq k\}.$$  

It is known that $3\text{-DNP}$ is NP-complete, whereas $2\text{-DNP}$ is in P; see Garey and Johnson [GJ79].
We now define the exact versions of domatic number problems.

**Definition 13 (Exact Domatic Number Problems)** Let $M_k$ be a set that consists of $k$ non-contiguous integers, and let $t$ be a positive integer. Define

- $\text{Exact-M}_k\text{-DNP} = \{G \mid G \text{ is a graph with } \delta(G) \in M_k\}$,
- $\text{Exact-t-DNP} = \{G \mid G \text{ is a graph with } \delta(G) = t\}$.

### 5.1 A General Framework for Dominating Set Problems

In order to investigate exact domatic number problems, we adopt Heggernes and Telle’s general, uniform approach to define graph problems by partitioning the vertex set of a graph into generalized dominating sets [HT98]. These are subsets of the vertex set of a given graph, parameterized by two sets of nonnegative integers, $\sigma$ and $\rho$, which restrict the number of neighbors for each vertex in the partition. Let $\mathbb{N} = \{0, 1, 2, \ldots\}$ denote the set of nonnegative integers, and let $\mathbb{N}^+ = \{1, 2, 3, \ldots\}$ denote the set of positive integers.

**Definition 14 (Heggernes and Telle)** Let $G$ be a given graph, let $\sigma \subseteq \mathbb{N}$ and $\rho \subseteq \mathbb{N}$ be given sets, and let $k \in \mathbb{N}^+$. Let $N(v) = \{w \in V(G) \mid \{v, w\} \in E(G)\}$ be the neighborhood of any vertex $v$ in $G$.

1. A subset $U \subseteq V(G)$ of the vertices of $G$ is said to be a $(\sigma, \rho)$-set if and only if
   
   - for each $u \in U$, $|N(u) \cap U| \in \sigma$, and
   - for each $u \notin U$, $|N(u) \cap U| \in \rho$.

2. A $(k, \sigma, \rho)$-partition of $G$ is a partition of $V(G)$ into $k$ pairwise disjoint subsets $V_1, V_2, \ldots, V_k$ such that $V_i$ is a $(\sigma, \rho)$-set for each $i$, $1 \leq i \leq k$.

3. Define the problem

   $$(k, \sigma, \rho)\text{-Partition} = \{G \mid G \text{ is a graph that has a } (k, \sigma, \rho)\text{-partition}\}.$$}

Note that $(k, \{0\}, \mathbb{N})\text{-Partition}$ is nothing other than $k\text{-Colorability}$, and $(k, \mathbb{N}, \mathbb{N}^+)\text{-Partition}$ is nothing other than $k\text{-DNP}$. This observation is illustrated by the following example. Note further that $(k, \{0\}, \mathbb{N})\text{-Partition}$ is a minimum problem, whereas $(k, \mathbb{N}, \mathbb{N}^+)\text{-Partition}$ is a maximum problem.

**Example 15 (Generalized Dominating Sets)** Figure 13 shows two copies of some graph $G$ with five vertices. Vertices labeled by the same number belong to the same $(\sigma, \rho)$-set, where either it is $\sigma = \{0\}$ and $\rho = \mathbb{N}$ (i.e., $k\text{-Colorability}$), or it is $\sigma = \mathbb{N}$ and $\rho = \mathbb{N}^+$ (i.e., $k\text{-DNP}$).

According to the partition into $(\sigma, \rho)$-sets shown on the left-hand side of Figure 13, $G$ is in the set $(4, \{0\}, \mathbb{N})\text{-Partition}$. That is, $G$ is a 4-colorable graph and the partition indicated corresponds to the four color classes of $G$.

In contrast, the partition into $(\sigma, \rho)$-sets on the right-hand side of Figure 13 shows that $G$ is in the set $(3, \mathbb{N}, \mathbb{N}^+)\text{-Partition}$. That is, $G$ has a domatic number of 3.
5.2 Summary of Results and Proof Ideas

Heggernes and Telle [HT98] obtained the NP-completeness results for \((k, \sigma, \rho)\)-Partition that are shown in Table 1. Here is the key: Table 1 gives the smallest value of \(k\) for which \((k, \sigma, \rho)\)-Partition is NP-complete, where

- "\(\infty\)" means that this problem is efficiently solvable for all values of \(k\);
- a superscript "\(+\)" indicates a maximum problem: For all \(k \geq 1\),
  \[(k + 1, \sigma, \rho)\)-Partition \(\subseteq\) \((k, \sigma, \rho)\)-Partition;

and

- a superscript "\(-\)" indicates a minimum problem: For all \(k \geq 1\),
  \((k, \sigma, \rho)\)-Partition \(\subseteq\) \((k + 1, \sigma, \rho)\)-Partition.

<table>
<thead>
<tr>
<th>(\sigma)</th>
<th>(\rho)</th>
<th>(\mathbb{N})</th>
<th>(\mathbb{N}^+)</th>
<th>({1})</th>
<th>({0,1})</th>
</tr>
</thead>
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<td>2</td>
<td>(\infty^-)</td>
<td></td>
</tr>
<tr>
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<td>2(^-)</td>
<td>2</td>
<td>3</td>
<td>3(^-)</td>
<td></td>
</tr>
<tr>
<td>({0,1})</td>
<td>2(^-)</td>
<td>2</td>
<td>3</td>
<td>3(^-)</td>
<td></td>
</tr>
<tr>
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<td>3(^-)</td>
<td>3</td>
<td>4</td>
<td>4(^-)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: NP-completeness for the problems \((k, \sigma, \rho)\)-Partition

We now define the exact versions of generalized dominating set problems.

**Definition 16 (Exact Partition Problems)** Define Exact-(\(k, \sigma, \rho\))-Partition, the exact version of the problem \((k, \sigma, \rho)\)-Partition, to be either

- \((k, \sigma, \rho)\)-Partition \(\cap\) \((k - 1, \sigma, \rho)\)-Partition if \((k, \sigma, \rho)\)-Partition is a minimum problem and \(k \geq 2\), or

\[\text{Figure 13: } (4, \{0\}, \mathbb{N})\text{-Partition (left) and } (3, \mathbb{N}, \mathbb{N}^+\text{-Partition (right)}\]
Theorem 17 (Riege and Rothe)

• $(k, \sigma, \rho)$-Partition $\cap (k+1, \sigma, \rho)$-Partition if $(k, \sigma, \rho)$-Partition is a maximum problem and $k \geq 1$.

Note that all Exact-$(k, \sigma, \rho)$-Partition problems are contained in DP. Note further that the specific problem Exact-$(k, \{0\}, N)$-Partition is nothing other than Exact-$k$-Colorability, and Exact-$(k, N, N^*)$-Partition is nothing other than Exact-$k$-DNP.

Table 2 gives the best values of $j$ $|$ $k$ for which it is known that the set Exact-$(k, \sigma, \rho)$-Partition is “(NP-complete or coNP-complete) $|$ DP-complete.” Again, “$\infty$” means that this problem is efficiently solvable for all values of $k$. Here, a dash “$-$” indicates that this problem is neither a maximum nor a minimum problem and thus is not considered.

Except the DP-completeness of Exact-$(k, \{0\}, N)$-Partition, which is presented here—using different notation—as Theorem 9 in Section 3 (see [Rot03]), all DP-completeness results in Table 2 are due to Riege and Rothe [RR04a]. We state the results from Table 2 in Theorem 17 below and provide the proof ideas. We do not attempt to give full, detailed proofs, though, referring to the original source [RR04a] instead.

<table>
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<tr>
<th>$\sigma$</th>
<th>$\rho$</th>
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<th>$N^*$</th>
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</tr>
<tr>
<td>${1}$</td>
<td>2 $</td>
<td>$ 5</td>
<td>$-$</td>
<td>3 $</td>
</tr>
<tr>
<td>${0, 1}$</td>
<td>2 $</td>
<td>$ 5</td>
<td>$-$</td>
<td>3 $</td>
</tr>
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<td>${0}$</td>
<td>3 $</td>
<td>$ 4</td>
<td>$-$</td>
<td>4 $</td>
</tr>
</tbody>
</table>

Table 2: DP-completeness for the problems Exact-$(k, \sigma, \rho)$-Partition

Theorem 17 (Riege and Rothe)

1. For each $i \geq 5$, Exact-$(i, N, N^*)$-Partition is DP-complete.
   In contrast, Exact-$(2, N, N^*)$-Partition is coNP-complete.

2. For each $i \geq 3$, Exact-$(i, N^*, N^*)$-Partition is DP-complete.
   In contrast, Exact-$(1, N^*, N^*)$-Partition is coNP-complete.

3. For each $i \geq 5$, Exact-$(i, \{0, 1\}, N)$-Partition is DP-complete.
   In contrast, Exact-$(2, \{0, 1\}, N)$-Partition is NP-complete.

4. For each $i \geq 5$, Exact-$(i, \{1\}, N)$-Partition is DP-complete.
   In contrast, Exact-$(2, \{1\}, N)$-Partition is NP-complete.

The proof of the first part of Theorem 17 uses the gadget shown in Figure 14 to provide a reduction from 3-Colorability that satisfies the hypothesis (2.2) of Wagner’s Lemma 7. The construction in Figure 14 extends Kaplan and Shamir’s reduction from 3-Colorability to 3-DNP with useful properties [KS94], see also [RR04a].

The proof of the second part of Theorem 17 uses the gadget shown in Figure 15 to provide a reduction from NAE-3-SAT that satisfies the hypothesis (2.2) of Wagner’s Lemma 7. The problem NAE-3-SAT (“not-all-equal satisfiability for boolean formulas with three literals per clause”) asks whether a given boolean formula $\varphi$ can be satisfied such that in none of the clauses of $\varphi$ all literals are true. Schaefer proved that NAE-3-SAT is NP-complete [Sch78]. The construction in Figure 15 is
inspired by Heggernes and Telle’s reduction from NAE-3-SAT to (2, N⁺, N⁺)-Partition, see [HT98] and also [RR04a].

The proof of the third part of Theorem 17 uses a reduction from 1-3-SAT that satisfies the hypothesis (2.2) of Wagner’s Lemma 7. The problem 1-3-SAT (“one-in-three satisfiability”) asks whether, given a boolean formula \( \varphi \), there exists a subset \( T \) of the literals of \( \varphi \) with \( |T \cap C_i| = 1 \) for each clause \( C_i \). Schaefer proved that 1-3-SAT is NP-complete, even if all literals in the given boolean formula are positive [Sch78].

Figure 16 shows this construction, which is based on Heggernes and Telle’s reduction from 1-3-SAT to (2, {0, 1}, N)-Partition, see [HT98]. The symbol \( \oplus \) in Figure 16 denotes the joint operation on graphs, i.e., for any two graphs \( G_1 \) and \( G_2 \), \( G_1 \oplus G_2 \) is the graph with vertex set
\[
V(G_1 \oplus G_2) = V(G_1) \cup V(G_2)
\]
and edge set

\[ E(G_1 \oplus G_2) = E(G_1) \cup E(G_2) \cup \{ \{a, b\} \mid a \in V(G_1) \text{ and } b \in V(G_2) \} \].

The proof of the fourth part of Theorem 17 is obtained by suitably modifying the proof of the third part of Theorem 17.

![Figure 16: Reduction to prove Exact-(5, \{0, 1\}, N)-Partition DP-complete](image)

Generalizing the results on exact generalized dominating set problems from Theorem 17, we obtain completeness results in the higher levels of the boolean hierarchy. In Theorem 18 below, we state this generalization for the problem \(\text{Exact}-M_k\)-\(\text{DNP}\) only, where \(M_k = \{4k+1, 4k+3, \ldots, 6k-1\}\). Analogously, the completeness results for \(\text{Exact}-(k, \sigma, \rho)\)-\(\text{Partition}\) given in the second, third, and fourth part of Theorem 17 can be lifted to the higher levels of the boolean hierarchy over \(\text{NP}\).

**Theorem 18 (Riege and Rothe)** For \(M_k = \{4k+1, 4k+3, \ldots, 6k-1\}\), \(\text{Exact}-M_k\)-\(\text{DNP}\) is \(\text{BH}_{2k}(\text{NP})\)-complete.

Finally, define the following variants of the domatic number problem:

\[
\begin{align*}
\text{DNP}_{\text{odd}} &= \{ G \mid G \text{ is a graph such that } \delta(G) \text{ is odd} \}, \\
\text{DNP}_{\text{equ}} &= \{ \langle G, H \rangle \mid G \text{ and } H \text{ are graphs with } \delta(G) = \delta(H) \}, \\
\text{DNP}_{\text{leq}} &= \{ \langle G, H \rangle \mid G \text{ and } H \text{ are graphs with } \delta(G) \leq \delta(H) \}.
\end{align*}
\]

**Theorem 19 (Riege and Rothe)** \(\text{DNP}_{\text{odd}}, \text{DNP}_{\text{equ}}, \text{ and } \text{DNP}_{\text{leq}} \) each are \(\Theta^p_2\)-complete.

### 6 Conclusions and Open Questions

This survey paper has presented some of the results that were inspired by Wagner's general technique [Wag87] to prove completeness in the levels of the boolean hierarchy over \(\text{NP}\) and in \(\Theta^p_2\), the class of problems solvable via parallel access to \(\text{NP}\). In particular, \(\Theta^p_2\)-completeness results were obtained for a variety of natural problems arising in computational politics [HHR97a, RSV03,
HH00, HSV05] and for problems related to certain approximation heuristics for hard graph problems [HR98, HRS06, HHR97b]. In addition, Wagner’s technique was useful to prove $\Theta_2^p$-hardness of MEE-DNF, the minimum equivalent expression problem, see Hemaspaandra and Wechsung [HW02] and also Umans [Uma98].

Turning to completeness in the levels of the boolean hierarchy, Theorem 9 in Section 3 answered a question raised by Wagner in [Wag87]: It is DP-complete to decide whether or not a given graph can be colored with exactly four colors. We have sketched Guriswami and Khanna’s clever reduction [GK00] that is central to this proof, and we have shown how this reduction can be employed by Wagner’s technique to prove Theorem 9.

In Section 4, we presented Cai and Meyer’s beautiful result that Minimal-3-Uncolorability is DP-complete [CM87]. It should be stressed here that it is usually very difficult to transfer known NP-completeness results to DP-completeness results for the corresponding critical problems. Papadimitrion and Yannakakis [PY84] note: “We have not been able to show that [...] any of the critical problems is DP-complete. This difficulty seems to reflect the extremely delicate and deep structure of critical problems—too delicate to sustain any of the known reduction methods. One way to understand this is that critical graphs is usually the object of hard theorems.” The crucial point is that polynomial-time many-one reductions from one problem to another do not preserve criticality in general. For this reason, only very few critical problems are known to be DP-complete up to date.

Finally, Section 5 studied various versions of the exact domatic number problem. In particular, Theorem 17 says that Exact-5-DNP is DP-complete. In contrast, Exact-2-DNP is coNP-complete, and thus this problem cannot be DP-complete unless the boolean hierarchy collapses. For $i \in \{3, 4\}$, the question of whether or not the problems Exact-$i$-DNP are DP-complete remains open. To close this gap, it would be enough to find a reduction from some suitable NP-complete problem to the exact domatic number problem that yields graphs having never a domatic number of three.

In addition, we have studied the exact versions of Heggernes and Telle’s generalized dominating set problems [HT98], denoted by Exact-$(k, \sigma, \rho)$-Partition, where the parameters $\sigma$ and $\rho$ specify the number of neighbors that are allowed for each vertex in the partition. Theorem 17 presented DP-completeness results for a number of such problems that are summarized in Table 2, which gives the best values of $k$ for which the problems Exact-$(k, \sigma, \rho)$-Partition are known to be DP-complete. This value of $k$ is not yet optimal in some cases. For example, as stated in Theorem 17, Exact-$(5, \{0, 1\}, \mathbb{N})$-Partition is DP-complete and Exact-$(2, \{0, 1\}, \mathbb{N})$-Partition is NP-complete. What about the complexity of Exact-$(i, \{0, 1\}, \mathbb{N})$-Partition for $i \in \{3, 4\}$? It would also be interesting to obtain DP-completeness results for those cases in Table 2 that currently have only question marks.

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References


