



A new method for counting chromatic coefficients

Halina Bielak*

*Institute of Mathematics, M. Curie-Skłodowska University,
pl. M. Curie-Skłodowskiej 1, 20-031 Lublin, Poland*

Abstract

In this paper, Proper-Broken-Cycle Formula is presented. The explicit expression in terms of induced subgraphs for the sixth coefficient of chromatic polynomial of a graph is presented. Also a new proof of Farrell's theorems is given.

1. Introduction

A very interesting relation between zeros of chromatic polynomials and some phenomena in theoretical physics is discovered (see [1,2] with references). It is well known that counting chromatic coefficients (i.e., coefficients of a chromatic polynomial) is important for location of chromatic zeros of graphs.

In this paper we propose a new method for counting chromatic coefficients. This method, called the Proper-Broken-Cycle Formula, is easier than the methods in [3-5]. The Proper-Broken-Cycle Formula can be simply applied for counting the explicit expression for the 4-th, 5-th and 6-th coefficients of the chromatic polynomial of a graph. We consider only simple graphs G with the vertex set $V(G)$ and the edge set $E(G)$. Let $P(G, \lambda)$ be the chromatic polynomial of a graph G . Let $\delta(G)$ be the minimum vertex degree of G . Whitney [5] gave an interpretation of chromatic coefficients of a graph using the concept of a broken cycle. Let $\beta : E(G) \rightarrow \{1, 2, \dots, q\}$ be a bijection where q is the size of G . Let C be a cycle of G . Suppose that e is an edge of the cycle C such that $\beta(e) > \beta(x)$ for any other edge x in C . Then the path $C-e$ is called a *broken cycle* in G induced by β .

Theorem 1 (Broken-Cycles Theorem [5]). *Let G be a graph of order n and size q , and let $\beta : E(G) \rightarrow \{1, 2, \dots, q\}$ be a bijection. Then*

*E-mail address: hbiel@golem.umcs.lublin.pl

$$P(G, \lambda) = \sum_{i=0}^{n-1} (-1)^i h_i \lambda^{n-i}, \tag{1}$$

where h_i is the number of spanning subgraphs of G that have exactly i edges and that contain no broken cycles induced by β .

Let G be an edge-labelled graph and let $\{B_1, B_2, \dots, B_\sigma\}$ be the set of broken cycles of G . Let B_{i_1, i_2, \dots, i_s} be the spanning subgraph of G whose edges are precisely those of G that belong to at least one of the broken cycles $B_{i_1}, B_{i_2}, \dots, B_{i_s}$. Then B_{i_1, i_2, \dots, i_s} is called a *minimal spanning subgraph of G containing s broken cycles*. Bari and Hall [3] using the principle of inclusion and exclusion and the concept of minimal spanning subgraph of G containing a number of broken cycles derived the following formula for coefficients of chromatic polynomial of a graph.

Theorem 2 (Bari-Hall Broken-Cycle Formula [3]). *Let G be an edge-labeled graph of order n and size q , and let $\{B_1, B_2, \dots, B_\sigma\}$ be the set of broken cycles of G induced by the given labeling. Then*

$$P(G, \lambda) = \sum_{i=0}^{n-1} (-1)^i h_i \lambda^{n-i} \tag{2}$$

and

$$h_i = \binom{q}{i} + \sum_{j=2}^i \binom{q-j}{i-j} \sum_{s=1}^{\sigma} (-1)^s n_{j,s}, \tag{3}$$

where σ is the number of broken cycles of G , and $n_{j,s}$ is the number of minimal spanning subgraphs of G with j edges and containing s broken cycles.

2. Proper-Broken-Cycle Formula. An application

Using the same method as that of Bari and Hall, we prove (in Theorem 3 below) that the set of *proper broken cycles* of G induced by the given labelling can be considered instead of the set of all broken cycles of G . Moreover, a family of edge-induced subgraphs can be considered instead of the family of minimal spanning subgraphs. These two facts reduce the number and order of subgraphs studied in the formula for chromatic coefficients of a given graph.

Let $\{B_1, B_2, \dots, B_\phi\}$ be the set of all proper broken cycles of G , where $\phi \leq \sigma$ and σ is the number of all broken cycles of G . Let P_{i_1, i_2, \dots, i_s} be an edge-induced subgraph of G generated by the set of all edges of proper broken cycles $B_{i_1}, B_{i_2}, \dots, B_{i_s}$, ($i_k \leq \phi$, $k = 1, \dots, s$). So P_{i_1, i_2, \dots, i_s} contains only the vertices of G that belong to an edge of at least one of $B_{i_1}, B_{i_2}, \dots, B_{i_s}$. Evidently, each vertex of P_{i_1, i_2, \dots, i_s} is incident to an edge of a proper broken cycle. For each $s=1, 2, \dots, \phi$, we

create the family of $\binom{\phi}{s}$ edge-induced subgraphs of the type P_{i_1, i_2, \dots, i_s} . Each graph P_{i_1, i_2, \dots, i_s} of the family we call a *minimal subgraph containing s proper broken cycles*. We can formulate the following theorem.

Theorem 3 (Proper-Broken-Cycle Formula). *Let G be an edge-labelled graph of the order n and the size q , and let $\{B_1, B_2, \dots, B_\phi\}$ be the set of all proper broken cycles of G induced by the given labeling. Then*

$$P(G, \lambda) = \sum_{i=0}^{n-1} (-1)^i h_i \lambda^{n-i}, \quad (4)$$

and

$$h_i = \binom{q}{i} + \sum_{j=2}^i \binom{q-j}{i-j} \sum_{s=1}^{\phi} (-1)^s g_{j,s}, \quad (5)$$

where ϕ is the number of proper broken cycles of G , and $g_{j,s}$ is the number of minimal subgraphs of G with j edges and containing s proper broken cycles of G .

Proof: First we introduce some notations. Let \mathcal{S} be the family of all spanning subgraphs with i edges of G , and let \mathcal{B} be the family of i - edge spanning subgraphs of G without broken cycles. Notice that \mathcal{B} is created from \mathcal{S} by deleting all elements containing a proper broken cycle. Let \mathcal{S}' be the family of graphs created from \mathcal{S} by deleting all isolated vertices from each graph of \mathcal{S} . (Evidently, if $i=0$ then \mathcal{S}' consists of the null graph (\emptyset, \emptyset)). Let \mathcal{B}' be the subfamily of \mathcal{S}' containing elements without proper broken cycles. Let N_i be the cardinality of \mathcal{S} and N'_i be the cardinality of \mathcal{S}' . Notice that $N_i = N'_i = \binom{q}{i}$. From Theorem 1 we have that h_i is the number of spanning subgraphs of G with i edges that contain no broken cycle. So $h_i = |\mathcal{B}| = |\mathcal{B}'|$. Let for a subgraph F of G , b_r be the property that F contains the broken cycle B_r , and \bar{b}_r be the property that F does not contain B_r , for $r \leq \sigma$. Similarly, let p_r be the property that F contains the proper broken cycle B_r , and \bar{p}_r be the property that F does not contain the proper broken cycle B_r , where $r \leq \phi$. Let $\{f_1, f_2, \dots, f_i\}$ be a set of properties of a graph. Let $N_i(f_1, f_2, \dots, f_i)$ be the number of spanning subgraphs of G with i edges and with properties f_1, f_2, \dots, f_i . Let $N'_i(f_1, f_2, \dots, f_i)$ be the number of elements of \mathcal{S}' with properties f_1, f_2, \dots, f_i . By Theorem 1 we get

$$h_i = N_i(\bar{b}_1, \bar{b}_2, \dots, \bar{b}_\sigma) = N_i(\bar{b}_1, \bar{b}_2, \dots, \bar{b}_\phi) = N'_i(\bar{p}_1, \bar{p}_2, \dots, \bar{p}_\phi). \quad (6)$$

Therefore by the inclusion - exclusion principle we get

$$\begin{aligned} h_i &= N_i - \left[N_i(b_1) + N_i(b_2) + \dots + N_i(b_\phi) \right] \\ &\quad + \left[N_i(b_1, b_2) + N_i(b_1, b_3) + \dots + N_i(b_{\phi-1}, b_\phi) \right] \\ &\quad + \dots + (-1)^\phi N_i(b_1, b_2, \dots, b_\phi) \\ &= N'_i - \left[N'_i(p_1) + N'_i(p_2) + \dots + N'_i(p_\phi) \right] \\ &\quad + \left[N'_i(p_1, p_2) + N'_i(p_1, p_3) + \dots + N'_i(p_{\phi-1}, p_\phi) \right] \\ &\quad + \dots + (-1)^\phi N'_i(p_1, p_2, \dots, p_\phi). \end{aligned}$$

The number of i -edge elements of the family \mathcal{S}' that contain a given j -edge subgraph F is $\binom{q-j}{i-j}$. Moreover, if $F = P_{i_1, i_2, \dots, i_s}$ then the term corresponding to F appears with the coefficient $(-1)^s$ in the above formula. Therefore, if there are $g_{j,s}$ subgraphs of G with j edges and the edge induced by s proper broken cycles, then they contribute $(-1)^s g_{j,s} \binom{q-j}{i-j}$ to h_i . The proof is done. □

In this paper we use Theorem 3 instead of Theorem 2. Let t_1 be the number of subgraphs isomorphic to K_3 in G . Let us assume that $T_i, i = 2, \dots, 31$ and $F_j, j = 0, 1, \dots, 11$ be graphs presented in Figures 1, 2 and 3.

Let $t_i, i = 2, \dots, 31$ (resp. $f_j, j = 0, 1, \dots, 11$), be the number of induced subgraphs of G isomorphic to T_i (resp. F_i). Farrell [4] proved the following two significant theorems concerning two coefficients of the chromatic polynomial of a graph.

Theorem 4[4]. *The coefficient of λ^{n-3} in $P(G, \lambda)$ is $-\binom{q}{3} + (q-2)t_1 + t_2 - 2t_3$.*

Theorem 5[4]. *The coefficient of λ^{n-4} in $P(G, \lambda)$ is*

$$\binom{q}{4} - \binom{q-2}{2} t_1 + \binom{t_1}{2} - (q-3) t_2 - (2q-9) t_3 - t_4 + t_5 + 2t_6 + 3t_7 - 6t_8.$$

Now we apply the Proper Broken-Cycle Formula presented in Theorem 3 to prove the above theorems in different and simpler way in comparison with the proof given in [4]. First we study properties of subgraphs of a graph G , involved in h_i , for $i = 2, 3, 4, \dots$

Let for a graph G , the numbers ϕ and $g_{j,s}$ be defined as in Theorem 3, and let

$$w_j(G) = \sum_{s=1}^{\phi} (-1)^s g_{j,s}. \text{ The number } w_j(G) \text{ we call the } j\text{-weight of the graph } G.$$

Proposition 6. Let F be an induced subgraph of G such that $\delta(F) = 1$. Then any spanning subgraph of F does not give its contribution to $w_j(G)$, for $j = 2, 3, \dots$

Proof: Let F be an induced subgraph of a graph G such that $\delta(F) = 1$. Let H be a spanning subgraph of F . Suppose that H is counted in j -weight of G . Then H has j edges and it is covered by a set of proper broken cycles. If H contains an edge incident to a 1-degree vertex in F , then this edge cannot belong to any broken cycle, a contradiction. Therefore H contains an isolated vertex, a contradiction (since, by definition of $g_{j,s}$, each vertex should be covered by an edge of a proper broken cycle). The proof is done. □

Proposition 7. *Let j be the integer, $2 \leq j$, and let F be an induced subgraph of G . If $|V(F)| > j + \lfloor \frac{j}{2} \rfloor$ then F is not covered by any set of proper broken cycles with j as the sum of their edges. Moreover, if $|E(F)| \leq j$ then $w_j(F) = 0, j = 2, 3, \dots$*

Proof: Note that F contains a vertex of degree at most 1. Thus the result follows immediately from Proposition 6 and Theorem 3. □

Proposition 8. *Let $2 \leq j$. Then $w_j(G) = \sum_F w_j(F)$, where the sum is taken over all induced subgraphs F of G with the minimum degree at least 2 and such that $|V(F)| \leq j + \lfloor \frac{j}{2} \rfloor$ and $|E(F)| > j$.*

Proof: Immediately from the definition of the broken cycle and from Propositions 6, 7. □

Immediately from Proposition 8 we have the following result.

Corollary 9. *For a graph G we get*

$$w_2(G) = w_2(T_1) \cdot t_1,$$

$$w_3(G) = w_3(T_2) \cdot t_2 + w_3(F_0) \cdot f_0 + w_3(T_3) \cdot t_3,$$

$$w_4(G) = \sum_F w_4(F), \text{ where the sum is taken over all induced subgraphs } F \text{ of}$$

G of the order 4,5,6 with $\delta(F) > 1$,

$$w_5(G) = \sum_F w_5(F), \text{ where the sum is taken over all induced subgraphs } F \text{ of}$$

G of the order 4,5,6,7 with $\delta(F) > 1$.

Proposition 10. *All weights are independent of an edge labelling of a graph.*

Proof: Immediately from the Proper Broken-Cycle Formula. □

Evidently, by Corollary 9, the 2-weights of G equals $-t_1$. Similarly 3-weights can be easily obtained. Notice that if a graph has at most 3 proper broken cycles

the 4-, and 5-weights can be easily obtained as well. The 4-, and 5-weights for other graphs we have been found by means of the computer computation. Table 1 contains the 3-,4-, and 5-weights for the graphs of the orders 4 and 5 with the minimum degree at least 2. Table 2 contains the 5-weights for the graphs of order 6 with the minimum degree at least 2.

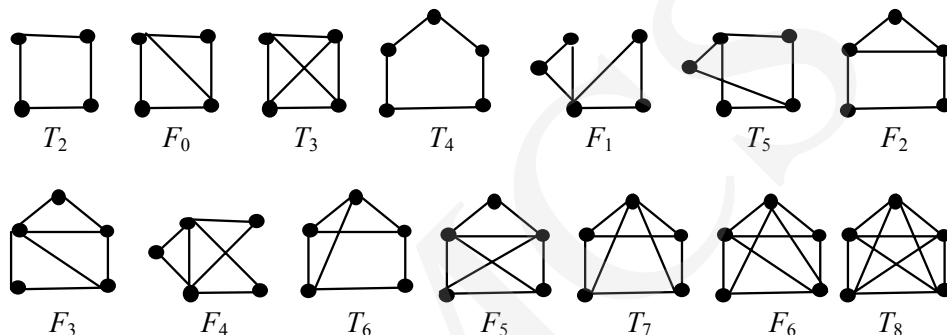


Fig. 1. The list of graphs of the orders 4 and 5 with minimum degree at least 2

In order to count h_i , for $i=4,5$, we use some special functions, defined below. Let D, F, H be the graphs of the orders 4, 5, 6, respectively. Let F_0, F_1, F_2, F_5 be the graphs presented in Fig. 1, and let F_7, F_8 be the graphs presented in Fig.3. We define two functions p, s for the graphs D and F , respectively as follows:

$p(D)$ = the number of spanning subgraphs of D isomorphic to F_0 ,

$s(F)$ = the number of spanning subgraphs of F isomorphic to F_1 .

Moreover, we define two functions u, z for F and two functions x, y for H as follows:

$u(F)$ = the number of spanning subgraphs of F isomorphic to F_2 , and such that the 4-cycles do not contain any chord in G ,

$z(F)$ = the number of spanning subgraphs of F isomorphic to F_5 ,

$x(H)$ = the number of spanning subgraphs of H isomorphic to F_7 , and such that the 4-cycles do not contain any chord in G ,

$y(H)$ = the number of spanning subgraphs of H isomorphic to F_8 .

The values of functions p, s, u, z are given in Table 1, and the values of functions x and y are given in Table 2, where $X=x(H)$ and $Y=y(H)$.

Proof: (of Theorems 4 and 5) We count h_3, h_4 from Theorem 3 and Corollary 9. Evidently $w_2(G) = -t_1$ and $w_3(G) = -t_2 + 2t_3$. Let $d_4 = \sum_H w_4(H)$, where the

sum is taken over all the induced subgraphs H of the order 6 in G and such that $\delta(H) > 1$. Note that the contribution of a graph H of the order 6 into 4-weight equals the number of spanning subgraphs of H isomorphic to $2K_3$. Therefore, from Table 1, we have

$$w_4(G) = d_4 + f_0 + 3t_3 - t_4 + f_1 + t_5 + f_3 + 2t_6 + 2f_5 + 5t_7 + 6f_6 + 9t_8.$$

Evidently, $w_4(F_0) = 1 = w_4(F_1) = w_4(2K_3)$ and $d_4 = \binom{t_1}{2} - \sum_D p(D) - \sum_F s(F)$,

where the sums are taken over all induced subgraphs D of the order 4 and all induced subgraphs F of the order 5 in G and such that $\delta(D) > 1$ and $\delta(F) > 1$.

Hence, $w_4(G) = \binom{t_1}{2} - 3t_3 - t_4 + t_5 + 2t_6 + 3t_7 - 6t_8$.

According to the Proper Broken-Cycle Formula presented in Theorem 3, we obtain h_3, h_4 .

Table 1. Graphs of the orders 4 and 5 with the minimum degree at least 2 and their j -weights, $j=3,4,5$, as well as their special functions

$F=$	T_2	F_0	T_3	T_4	F_1	T_5	F_2	F_3	F_4	T_6	F_5	T_7	F_6	T_8
$w_3(F)$	-1	0	2	0	0	0	0	0	0	0	0	0	0	0
$w_4(F)$	0	1	3	-1	1	1	0	1	0	2	2	5	6	9
$w_5(F)$	0	0	-2	0	0	1	1	0	0	2	-2	-2	-12	-36
$p(F)$	0	1	6											
$s(F)$				0	1	0	0	1	0	0	2	2	6	15
$u(F)$				0	0	0	1	0	0	2	0	4	0	0
$z(F)$				0	0	0	0	0	0	0	1	0	6	30

□

The following theorem presents the sixth chromatic coefficient for a graph G .

Theorem 11. *The coefficient of λ^{n-5} in $P(G, \lambda)$ is $(-1)h_5$, where*

$$h_5 = \binom{q}{5} - \binom{q-2}{3}t_1 + (q-4)\binom{t_1}{2} - \binom{q-3}{2}t_2 + (t_2 - 2t_3)t_1 + (q^2 - 10q + 30)t_3 - t_4 + (q-3)t_5 + 2(q-5)t_6 + 3(q-6)t_7 - 6(q-8)t_8 - t_9 + t_{10} + 2t_{11} + 2t_{12} + t_{13} - t_{14} + t_{15} + 3t_{16} + 4t_{17} + 4t_{18} - 2t_{19} + 4t_{20} + t_{21} - 4t_{22} - 3t_{23} - 4t_{24} - 5t_{25} - 4t_{26} - 6t_{27} - 8t_{28} - 16t_{29} - 12t_{30} + 24t_{31},$$

Where t_1 is the number of K_3 in G and $t_i, i=2, \dots, 28$, are the numbers of subgraphs of G isomorphic to graphs T_i presented in Figures 1-2.

Proof: Using Theorem 3 and Corollary 9 we count h_5 . Let $d_5 = \sum_F w_5(F)$,

where the sum is taken over all induced subgraphs F of the order 7 in G such that $\delta(F) > 1$. Let F_9, F_{10}, F_{11} be the graphs presented in Fig. 3. Notice that

$$w_5(F_{10}) = 0, w_5(F_9) = 1, w_5(F_{11}) = -2.$$

Therefore

$$d_5 = t_1 \cdot t_2 - 2 \cdot t_1 \cdot t_3 + 2 \cdot 4 \cdot t_3 - \sum_F (u(F) - 2z(F)) + \sum_H (2y(H) - x(H)),$$

where the sums are taken over all induced subgraphs F of the order 5 and all induced subgraphs H of the order 6 in G , with $\delta(F) > 1$ and $\delta(H) > 1$.

From Proposition 8 and Corollary 9, we have

$$w_5(G) = d_5 + t_3 \cdot w_5(T_3) + \sum_F w_5(F) + \sum_H w_5(H),$$

where the sums are taken over all induced subgraphs F of the order 5 and all induced subgraphs H of the order 6 in G , with $\delta(F) > 1$ and $\delta(H) > 1$. Hence, from Theorem 3, we get

$$\begin{aligned} h_5 = & \binom{q}{5} - \binom{q-2}{3} \cdot t_1 + \binom{q-3}{2} (-t_2 + 2t_3) + (q-4) \left(\binom{t_1}{2} - 3t_3 - t_4 + t_5 + 2t_6 + 3t_7 - 6t_8 \right) \\ & + t_1 \cdot t_2 - 2t_1 \cdot t_3 + 6t_3 + t_5 - 6t_7 + 24t_8 - t_9 + t_{10} + 2t_{11} + 2t_{12} + t_{13} - t_{14} + t_{15} \\ & + 3t_{16} + 4t_{17} + 4t_{18} - 2t_{19} + 4t_{20} + t_{21} - 4t_{22} - 3t_{23} - 4t_{24} - 5t_{25} - 4t_{26} - 6t_{27} \\ & - 8t_{28} - 16t_{29} - 12t_{30} + 24t_{31}. \end{aligned}$$

Finally, from the simple algebraic reduction, we get the result. □

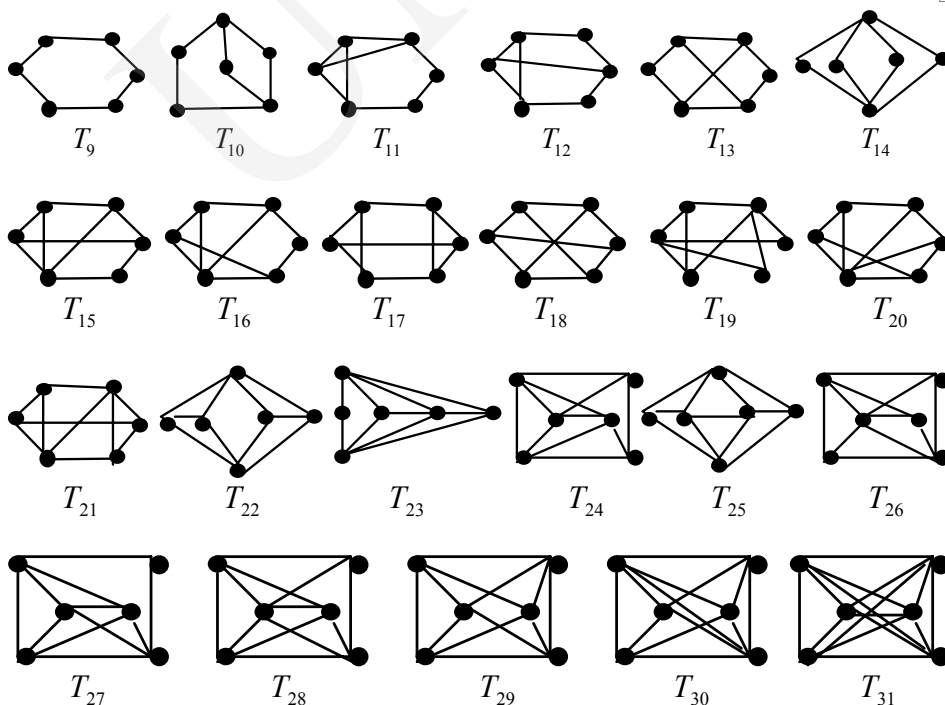


Fig. 2. The list of graphs of the order 6 with the minimum degree at least 2 present in h_5

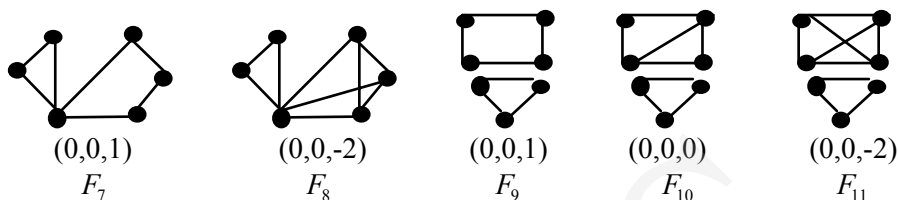


Fig. 3. Other graphs of the minimum degree 2 and the order 6 or 7 with their 3-, 4- and 5-weights

The following Table 2 contains the adjacency matrices of graphs H of the order 6 with the minimum degree at least 2 and their 5-weights (**bold**, in the right upper corner), where $X=x(H)$, $Y=y(H)$.

Table 2. The adjacency matrices of graphs H of the order 6 with the minimum degree at least 2 and their 5-weights (**bold**, in the right upper corner), where $X=x(H)$, $Y=y(H)$

$T_{31} : \mathbf{-96}$	$\mathbf{-48}$	$\mathbf{18}$	$T_{30} : \mathbf{-24}$	$T_{29} : \mathbf{-16}$	$\mathbf{0}$	$T_{28} : \mathbf{-6}$	$\mathbf{-4}$
011111	001111	000111	001111	001111	000111	000111	000011
101111	001111	001111	001111	001111	000111	001111	001111
110111	110111	010111	110011	110011	000111	010111	010111
111011	111011	111011	110011	110011	111011	111001	011011
111101	111101	111101	111101	111100	111101	111001	111101
111110	111110	111110	111110	111100	111110	111110	111110
$X=0 Y=60$	$X=0 Y=24$	$X=0 Y=9$	$X=4 Y=8$	$X=0 Y=0$	$X=0 Y=0$	$X=6 Y=2$	$X=0 Y=2$
$\mathbf{-8}$	$T_{27} : \mathbf{3}$	$\mathbf{-2}$	$\mathbf{0}$	$T_{26} : \mathbf{2}$	$\mathbf{-8}$	$\mathbf{0}$	$T_{25} : \mathbf{-3}$
000111	000011	000011	000011	000111	000111	000111	000111
001011	001111	001111	000111	000111	001011	001011	001011
010111	010111	010111	000111	000111	010011	010111	010111
101011	011011	011001	011011	111001	100011	101001	101011
111101	111100	111001	111101	111001	111101	111001	111100
111110	111100	111110	111110	111110	111110	111110	111100
$X=0 Y=4$	$X=9 Y=0$	$X=0 Y=1$	$X=0 Y=0$	$X=6 Y=0$	$X=0 Y=4$	$X=2 Y=1$	$X=2 Y=0$
$T_{24} : \mathbf{4}$	$\mathbf{4}$	$\mathbf{-2}$	$\mathbf{0}$	$\mathbf{0}$	$\mathbf{1}$	$T_{23} : \mathbf{1}$	$\mathbf{0}$
000111	000011	000101	000011	000011	000011	000011	000011
001111	001101	001011	001101	000101	000111	000111	000011
010111	010111	010011	010110	000111	000111	000111	000111
111000	011011	100011	011011	011011	011001	011011	001011
111001	101100	011101	101101	101101	111001	111100	111101
111010	111100	111110	110110	111110	111110	111100	111110
$X=8 Y=0$	$X=4 Y=0$	$X=0 Y=1$	$X=0 Y=0$	$X=0 Y=0$	$X=1 Y=0$	$X=4 Y=0$	$X=0 Y=0$

0	6	$T_{22} : -4$	$T_{21} : 3$	$T_{20} : 4$	0	$T_{19} : 0$	0
000011	000111	000111	001111	001101	000011	000011	000011
001100	000111	001011	000111	000111	000011	000011	000011
010111	000111	010011	100011	100011	000011	000111	000110
011011	111000	100011	110001	110001	000011	001011	001011
101101	111001	111100	111000	011001	111101	111100	111101
101110	111010	111100	111100	111110	111110	111100	110110
X=0 Y=0	X=6 Y=0	X=0 Y=0	X=2 Y=0	X=0 Y=0	X=0 Y=0	X=2 Y=0	X=0 Y=0
0	0	1	2	$T_{18} : 4$	$T_{17} : 4$	$F_8 : -2$	2
000011	000011	000011	000011	000111	001110	001001	001010
000101	000110	000110	000111	000111	000111	000111	000111
000110	000111	000111	000111	000111	100011	100001	100001
011010	011010	011001	011000	111000	110001	010011	010011
101101	111101	111001	111001	111000	111000	010101	110101
110110	101010	101110	111010	111000	011100	111110	011110
X=0 Y=0	X=0 Y=0	X=1 Y=0	X=2 Y=0	X=0 Y=0	X=0 Y=0	X=0 Y=1	X=2 Y=0
0	0	$T_{16} : 4$	$T_{15} : 3$	$T_{14} : -1$	0	0	1
001010	001010	001100	000011	011101	011000	010010	011000
000101	000111	000111	000111	100010	101000	100010	101011
100011	100011	100011	000111	100010	110011	000011	110100
010011	010011	110001	011001	100010	000011	000011	001011
101101	111100	011001	111000	011101	001101	111101	010100
011110	011100	011110	111100	100010	001110	001110	010100
X=0 Y=0	X=0 Y=0	X=1 Y=0	X=2 Y=0	X=0 Y=0	X=0 Y=0	X=0 Y=0	X=1 Y=0
0	$T_{13} : 1$	$T_{12} : 2$	$T_{11} : 2$	0	0	1	0
000011	001100	000101	011000	011000	011001	011000	011000
000011	000011	000011	100001	101001	100001	100001	100001
000110	100011	000111	100110	110100	100100	100101	100101
001001	100011	101010	001011	001011	001011	001011	001010
111001	011100	011100	001101	000101	000101	000101	000101
110110	011100	111000	010110	010110	110110	011110	011010
X=0 Y=0	X=0 Y=0	X=0 Y=0	X=0 Y=0	X=0 Y=0	X=0 Y=0	X=1 Y=0	X=0 Y=0
0	$T_{10} : 1$	$F_7 : 1$	0	$T_9 : -1$			
011100	011001	011000	011000	011000			
101000	100100	101000	100001	100001			
110000	100010	110101	100100	100100			
100011	010010	001010	001011	001010			
000101	001101	000101	000101	000101			
000110	100010	001010	010110	010010			
X=0 Y=0	X=0 Y=0	X=1 Y=0	X=0 Y=0	X=0 Y=0			

3. Final remarks

The values of h_5 , h_4 can be applied to study sufficient conditions for the existence of complex roots of chromatic polynomials. The conditions in terms h_2 , h_3 are presented in [6] and [7], respectively. The new Proper-Broken-Cycle

Formula presented in Theorem 3 can be simply applied for counting explicit expression for the next coefficients of chromatic polynomial of a graph.

References

- [1] Sokal A.D., *Bounds on the Complex Zeros of (di)chromatic Polynomials and Potts-model Partition Functions*, *Combin., Probab. Comput.*, 10 (2001) 41.
- [2] Sokal A.D., *Chromatic Roots are Dense in the Whole Complex Plane*, *Combin., Probab. Comput.*, 13(2) (2004) 221.
- [3] Bari R.A., Hall D.W., *Chromatic Polynomials and Whitney's broken circuits*, *Journal of Graph Theory*, 1 (1977) 269.
- [4] Farrell E.J., *On chromatic coefficients*, *Discrete Mathematics*, 29 (1980) 257.
- [5] Whitney H., *A logical expansion in mathematics*, *Bull. Amer. Math. Soc.*, 38 (1932) 572.
- [6] Brown J., *On roots of chromatic polynomials*, *J. Combin. Theory S.B.*, 72 (1998) 251.
- [7] Bielak H., *Roots of chromatic polynomials*, *Discrete Mathematics*, 231 (2001) 97.