ASSOCIATIVE SPECTRA OF GRAPH ALGEBRAS II.
SATISFACTION OF BRACKETING IDENTITIES,
SPECTRUM DICHOTOMY

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Abstract. A necessary and sufficient condition is presented for a graph algebra to satisfy a bracketing identity. The associative spectrum of an arbitrary graph algebra is shown to be either constant or exponentially growing.

6. Introduction to Part II

This paper continues our study, initiated in [2], of associative spectra of graph algebras. Introduced by Csákány and Waldhauser [1], the associative spectrum of a binary operation or of the corresponding groupoid is a method of quantifying the degree of (non)-associativity of the operation. Graph algebras were introduced by Shallon [4] as a way of encoding an arbitrary directed graph as an algebra with a binary operation. We refer the reader to the first part of this study [2] – henceforth called “Part I” – for formal definitions, background, motivations, and further details that will not be repeated in this outline. We continue the numbering of sections from Part I, so that we can conveniently refer to theorems, definitions, etc. of Part I simply by their numbers.

In Part I, we determined the possible associative spectra of undirected graphs and classified undirected graphs by their spectra; there are only three distinct possibilities: constant 1, powers of 2, and Catalan numbers. Furthermore, we characterized the antiassociative digraphs, and we determined the associative spectra of certain families of digraphs, such as paths, cycles, and graphs on two vertices.

In this paper, we turn our attention to graph algebras associated with arbitrary digraphs, which may be finite or infinite. In Section 7, we provide a necessary and sufficient condition for a graph algebra to satisfy a nontrivial bracketing identity. The condition is expressed in terms of several numerical structural parameters associated, on the one hand, with the digraph and, on the other hand, with a pair of bracketings. We discuss in Section 8 how some of the results of Part I are obtained as special cases of this condition.

This result seems a first step towards a general description of the associative spectra of graph algebras associated with arbitrary digraphs. Such a general result, however, eludes us. We can nevertheless establish bounds for the possible associative spectra of graph algebras. As we will see in Section 9, the associative spectrum of a graph algebra is either a constant sequence bounded above by 2 or it grows exponentially, the least possible growth rate of an exponential spectrum being \( \alpha^n \), where \( \alpha \approx 1.755 \) is the following cubic algebraic integer:

\[
\alpha = \frac{1}{3} \sqrt[3]{\frac{25 + 3\sqrt{69}}{2}} + \frac{1}{3} \sqrt[3]{\frac{25 - 3\sqrt{69}}{2}} + \frac{2}{3}.
\]

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This stands in stark contrast with associative spectra of arbitrary groupoids, where various subexponential spectra such as polynomials of arbitrary degrees are possible.

7. Satisfaction of bracketing identities by digraphs

We now turn to the general case of arbitrary directed graphs. We are going to define several numerical parameters pertaining, on the one hand, to a pair of distinct bracketing terms \( t, t' \in B_n \) and, on the other hand, to a digraph \( G \). For easy reference, the various parameters are collected in Table 1 with cross-references to their definitions. With the help of these parameters, we can provide necessary and sufficient conditions for the graph algebra of a digraph to satisfy a bracketing identity. These conditions are put together in Theorem 7.31.

Recall the parameters \( H_{t,t'} \), \( M_{t,t'} \), and \( L_{t,t'} \) from Definition 4.2. The following lemma extends Lemma 4.4.

**Lemma 7.1.** Let \( t, t' \in B_n \), \( t \neq t' \), and let \( G \) be a digraph such that \( A(G) \) satisfies the identity \( t \approx t' \). Denote \( H \seteq H_{t,t'} \), \( M \seteq M_{t,t'} \), \( L \seteq L_{t,t'} \). Let \( r \) be the integer provided by Lemma 4.4. Then there exists an integer \( s \) with \( L + 1 \leq s \leq r \) and \( s \equiv L \) (mod \( M \)) such that the following holds: if \( v_0 \to v_1 \to \cdots \to v_H \) and \( v_L \to v_{L+1} \to v_{L+2} \to \cdots \to v_H \) are walks in \( G \), then \( v_r \to v_{L+1} \) and \( v_r \to v_{L+1} \) are edges in \( G \). In particular, \( v_{L+1} \) and \( v'_{L+1} \) belong to the same nontrivially strongly connected component.

**Proof.** By the definition of \( L \), there exists a vertex \( x_d \in X_n \) such that either \( d_T(x_d) = L + 1 < d_T(x_d) \) or \( d_T(x_d) = L + 1 < d_T(x_d) \). By changing the roles of \( T \) and \( T' \), if necessary, we may assume that \( d_T(x_d) = L + 1 < d_T(x_d) \). Let \( x_p \) be the parent of \( x_d \) in \( T \), and let \( x_q \) be the parent of \( x_d \) in \( T' \).

Assume that \( v_0 \to v_1 \to \cdots \to v_H \) and \( v_L \to v_{L+1} \to v_{L+2} \to \cdots \to v_H \) are walks in \( G \). By Lemma 4.4, \( v_r \to v_{L+1} \) and \( v'_r \to v'_{L+1} \) are edges, so \( v_{L+1} \to \cdots \to v_r \to v_{L+1} \) and \( v'_L \to \cdots \to v'_r \to v'_{L+1} \) are closed walks in \( G \). Let \( W \) be the walk that starts with \( v_0 \to \cdots \to v_L \) and continues by going around the closed walk \( v_{L+1} \to \cdots \to v_r \to v_{L+1} \) until it reaches length \( h(T) \), and let \( W' \) be the closed walk \( v'_{L+1} \to \cdots \to v'_{L+1} \). Let \( \varphi \colon X_n \to V(G) \) be the collapsing map of \( (T, x_d) \) on \( (W, W') \). Since \( \varphi \) is a homomorphism of \( T \) into \( G \), it is also a homomorphism of \( T' \) into \( G \) by Proposition 2.1. Since \( (x_q, x_d) \in E(T') \), we have \( (\varphi(x_q), \varphi(x_d)) \in E(G) \). By definition, \( \varphi(x_d) = v'_{L+1} \). In order to determine \( \varphi(x_d) \), note first that \( q < d \) because \( (x_q, x_d) \) is an edge in \( T' \). This implies that \( x_q \notin T_{x_d} \) and thus \( \varphi(x_d) \) lies in \( W \), so \( \varphi(x_q) = \chi_s \) for some \( s \in \{0, 1, \ldots, r\} \). Since \( d_T(x_d) \geq L + 1 \), \( \varphi(x_q) \) lies on the closed walk \( v_{L+1} \to \cdots \to v_r \to v_{L+1} \). Therefore \( s \) is the unique element of the set \( \{L + 1, \ldots, r\} \) such that \( s \equiv d_T(x_q) \) (mod \( r - L \)); note that the value of \( s \) does

| parameter | Definition | parameter | Definition |
|-----------|------------|-----------|------------|
| \( H_{t,t'} \) | 4.2 | \( M_G \) | 7.2 |
| \( M_{t,t'} \) | 4.2 | \( P_G \) | 7.4 |
| \( I_{t,t'} \) | 4.2 | \( E_G \) | 7.4 |
| \( Y_{t,t'} \) | 7.6 | \( O_G \) | 7.4 |
| \( Z_{t,t'} \) | 7.11 | \( Z_G \) | 7.14 |
| \( \omega_{t,t'} \) | 7.28 | \( B_G \) | 7.14 |
| \( \lambda_{t,t'} \) | 7.45 | \( \omega_G \) | 7.22 |

Table 1. Parameters of pairs of bracketings and graphs.
not depend on the walks \( v_0 \to v_1 \to \cdots \to v_H \) and \( v_L \to v'_L \to v'_L+2 \to \cdots \to v'_H \),
but only on \( t \) and \( t' \). Since \( r \equiv L \pmod{M} \), the number \( r - L \) is divisible by \( M \);
therefore \( s \equiv d_T(x_q) \equiv L \pmod{M} \).

Switching the roles of the closed walks \( v_{L+1} \to \cdots \to v_r \to v_{L+1} \) and \( v'_{L+1} \to \cdots \to v'_{r} \to v'_{L+1} \),
a similar argument shows that \( (v'_s, v_{L+1}) \in E(G) \). Now we have
the closed walk \( v_{L+1} \to \cdots \to v_s \to v'_L \to v'_L+2 \to \cdots \to v'_s \to v_{L+1} \) in \( G \). This means,
in particular, that \( v_{L+1} \) and \( v'_{L+1} \) belong to the same nontrivial strongly connected component.

\[ \square \]

**Definition 7.2.** For a digraph \( G \), let \( M_G \) be the least common multiple of the set
of all numbers \( m \) for which there exists a strongly connected component of \( G \) that
is an \( m \)-whirl, with the convention that the least common multiple of the empty set
is 1. If there is no finite upper bound on such numbers \( m \), then define \( M_G := \infty \).

**Example 7.3.** Consider the graph \( G \) shown in Figure 1. Highlighted as shaded
regions, the nontrivial strongly connected components are a 3-whirl and a 4-whirl.
Consequently, \( M_G = \text{lcm}(3, 4) = 12 \).

**Definition 7.4.** Let \( G = (V, E) \) be a digraph. Recall that a walk in \( G \) is **pleasant**,
if all its vertices belong to trivial strongly connected components. A walk in \( G \) is **winding**, if all its vertices belong to a single nontrivial strongly connected component
of \( G \).
Lemma 7.6. Let $K$ be a nontrivial strongly connected component of $G$. A path $v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_t$ in $G$ is called an entryway to $K$ if $v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_{t-1}$ is a pleasant path and $v_t \in K$. Analogously, $v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_t$ is called an outlet from $K$ if $v_0 \in K$ and $v_1 \rightarrow v_2 \rightarrow \cdots \rightarrow v_t$ is a pleasant path.

Denote by $P_G$, $E_G$ and $O_G$ the length of the longest pleasant path, entryway, and outlet in $G$, respectively. If there is no finite upper bound on the length of pleasant paths, entryways, or outlets in $G$, then define $P_G := \infty$, $E_G := \infty$, $O_G := \infty$, respectively. If there is no pleasant path, entryway, or outlet in $G$, then let $P_G := -\infty$, $E_G := -\infty$, $O_G := -\infty$, respectively.

Example 7.5. In the graph $G$ of Figure 1, the longest pleasant path is $p_0 \rightarrow p_1 \rightarrow \cdots \rightarrow p_9$, the longest entryway is $e_0 \rightarrow e_1 \rightarrow e_2 \rightarrow e_3 \rightarrow e_4$, and the longest outlet is $o_0 \rightarrow o_1 \rightarrow o_2 \rightarrow o_3$. Therefore, $P_G = 9$, $E_G = 4$, $O_G = 3$.

Lemma 7.6. If a digraph $G$ satisfies the identity $t \approx t'$ for $t, t' \in B_n$, $t \neq t'$, then $M_G|M_{t,t'}$ and $P_G < H_{t,t'}$.

Proof. This follows immediately from Lemmata 4.8 and 4.11. □

Lemma 7.7. Let $t, t' \in B_n$, $t \neq t'$, and let $G$ be a digraph such $h(G)$ satisfies the identity $t \approx t'$. Then $E_G \leq L_{t,t'} + 1$.

Proof. Denote $H := H_{t,t'}$, $L := L_{t,t'}$. Suppose, to the contrary, that there is an entryway $W: v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_k$, where $k > L + 1$. Then $v_k$ belongs to a nontrivial strongly connected component $K$ and the other vertices of $W$ belong to trivially strongly connected components. Extending $W$, if necessary, with vertices of $K$, we obtain a walk $v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_H$, and Lemma 4.4 implies that $v_{L+1}$ belongs to a nontrivial strongly connected component. This is a contradiction. □

Definition 7.8. Let $t, t' \in B_n$, $t \neq t'$, and denote $T := G(t)$, $T' := G(t')$. Let $Y_{t,t'}$ be the largest integer $m$ such that for all $x_i \in X_n$,

$$h(T_{x_i}) \leq m \vee h(T'_{x_i}) \leq m \implies T_{x_i} = T'_{x_i}$$

In other words, the rooted induced subtrees of $T$ and $T'$ of height at most $Y_{t,t'}$ are identical. Note that $-1 \leq Y_{t,t'} < H_{t,t'}$, and the equality $Y_{t,t'} = -1$ holds if and only if $T$ and $T'$ have different sets of leaves.

Example 7.9. Figure 2 shows two DFS trees corresponding to certain terms $t, t' \in B_{14}$. It is easy to verify that $Y_{t,t'} = 3$: all subtrees of height at most 3 are identical in the two trees, but the subtrees rooted at $x_3$ are distinct and have height 4.
Lemma 7.10. Let $t, t' \in B_n$, $t \neq t'$, and let $G$ be a digraph such that $\mathbb{A}(G)$ satisfies the identity $t \sim t'$. Then $O_t \leq Y_{t,t'} + 1$.

Proof. Denote $Y := Y_{t,t'}$. By the definition of $Y$, there exists $x_d \in X_n$ such that $T_{x_d} \neq T_{x_d}'$, and $h(T_{x_d}) = Y + 1 \leq h(T_{x_d}')$ or $h(T_{x_d}) = Y + 1 \leq h(T_{x_d}')$. We may assume, by changing the roles of $t$ and $t'$ if necessary, that $h(T_{x_d}) = Y + 1 \leq h(T_{x_d}')$.

By the definition of a DFS tree, $V(T_{x_d}) = X[\ell,e]$ and $V(T_{x_d}') = X[\ell',e']$ for some $\ell, \ell' \in [n]$. Assume that $N^T_0(x_d) = \{x_1, x_2, \ldots, x_i\}$ with $d+1 = i < i_2 < \cdots < i_t$; hence $V(T_{x_i}) = X[i,i+j-1]$ for $1 \leq j \leq \ell - 1$ and $V(T_{x_i}) = X[\ell,e]$ for $j = \ell$.

For all $x_i \in N^T_0(x_d)$ it holds that $h(T_{x_i}) \leq h(T_{x_d}) - 1 = Y$; hence $T_{x_i} = T_{x_i}'$ by the definition of $Y$. For all $x_i \in N^T_0(x_d)$ with $i < e'$, we obviously have $x_i \notin V(T_{x_i}')$ and hence $x_i \notin N^T_0(x_d)$. An easy inductive argument shows that $x_i \in N^T_0(x_d)$ for all $x_i \in N^T_0(x_d)$ with $i \leq e'$.

We must have $e \neq e'$. (Suppose, to the contrary, that $e = e'$. Then $N^T_0(x_d) = N^T_0(x_d)$ and consequently $T_{x_d} = T_{x_d}'$, contradicting our assumptions.) If $e < e'$, then $N^T_0(x_d) \subseteq N^T_0(x_d)$; in particular, $x_{e+1} \in N^T_0(x_d)$. If $e > e'$, then $N^T_0(x_d) \supsetneq N^T_0(x_d)$; in particular, $x_{e+1} \in N^T_0(x_d)$.

Suppose, to the contrary, that $G$ has an outlet $W: v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_k$ with $k > Y + 1$. Then $v_0$ belongs to a nontrivial strongly connected component $K$ and the remaining vertices of $W$ belong to trivially strongly connected components. In particular, there exists a cycle $C$ in $K$ to which $v_0$ belongs.

Consider first the case when $e < e'$. Let $W': v_1 \rightarrow \cdots \rightarrow v_k$, let $x_{d'}$ be the parent of $x_d$ in $T$, and let $\varphi: X_n \rightarrow V(G)$ be the collapsing map of $(T, x_d)$ on $(C, W')$ satisfying $\varphi(x_{d'}) = v_0$. By Proposition 2.1, $\varphi$ is a homomorphism of $T'$ into $G$. Since $(x_d, x_{e+1})$ is an edge of $T'$, we have the edge $(\varphi(x_d), \varphi(x_{e+1})) \in E(G)$. Since $\varphi(x_d) = v_1$ and $\varphi(x_{e+1})$ belongs to $C$, this implies that $v_1$ belongs to the strongly connected component $K$, a contradiction.

The case when $e > e'$ is treated similarly. Let $W': v_1 \rightarrow \cdots \rightarrow v_k$, let $x_{d'}$ be the parent of $x_d$ in $T'$, and let $\varphi: X_n \rightarrow V(G)$ be the collapsing map of $(T', x_d)$ on $(C, W')$ satisfying $\varphi(x_{d'}) = v_0$. Note that in this case $h(T_{x_d}) = h(T_{x_d}) = Y + 1 < k$, so it is indeed possible to collapse $T_{x_d}$ on $v_1 \rightarrow \cdots \rightarrow v_k$. A similar argument as above now shows that $(\varphi(x_d), \varphi(x_{e+1})) \in E(G)$, which implies that $v_1$ belongs to the strongly connected component $K$, a contradiction.("Define 7.11. Let $t, t' \in B_n$, $t \neq t'$, and denote $T := G(t)$, $T' := G(t')$. Let $Z_{t,t'}$ be the smallest nonnegative number $m$ such that there exists $x_{d'} \in X_n$ with $T_{x_{d'}} = T_{x_{d'}}'$, $h(T_{x_{d'}}) = h(T_{x_{d'}}') = m$, and $x_{d'}$ has distinct parents in $T$ and $T'$. Such a number $m$ always exists (see Lemma 7.12 below) and it must clearly be smaller than the heights of $T$ and $T'$. Hence $0 \leq Z_{t,t'} < H_{t,t'}$.

Example 7.12. For the DFS trees of Figure 2, it holds that $Z_{t,t'} = 2$, as witnessed by the subtrees rooted at $x_{d'}$.

The next lemma shows that the parameter $Z_{t,t'}$ is well defined: for distinct DFS trees $T$ and $T'$ of size $n$, there always exists a vertex $x_i \in X_n$ such that $T_{x_i} = T_{x_i}'$, and $x_i$ has distinct parents in $T$ and $T'$.

Lemma 7.13. Let $T$ and $T'$ be DFS trees of size $n$. Assume that for all $x_i \in X_n \setminus \{x_1\}$, it holds that if $T_{x_i} = T_{x_i}'$, then $x_i$ has the same parent in $T$ and in $T'$. Then $T = T'$.

Proof. We proceed by induction on $n$. The statement obviously holds for $n = 1$ and $n = 2$. Assume that the statement holds for all DFS trees of size $k$. Let $T$ and $T'$ be DFS trees of size $k + 1$ satisfying the condition that for all $x_i \in X_{k+1} \setminus \{x_1\}$, if $T_{x_i} = T_{x_i}'$, then $x_i$ has the same parent in $T$ and $T'$.\]
If there is no finite upper bound on such numbers \( x \), then define \( \bar{t} = T \). Clearly \( T \) and \( \bar{T} \) are DFS trees of size \( k \), and \( T = T'(x_0, x_k + 1) \) and \( \bar{T}' = T'(x, x_k + 1) \) (where the notation \( T'(x_0, x_k + 1) \) stands for adjoining a new vertex \( x_k + 1 \) and a new edge \((x_0, x_k + 1)\) to \( T \)). Let \( x \in X_k \) and assume that \( T_{x_i} = \bar{T}_{x_i}' \).

Example 7.15. In the graph \( G \) of Figure II vertices \( u \) and \( w \) belong to the same block of a whirl. The path \( u \to z_0 \to z_1 \) and the non-edge \((w, z_0)\) witness that \( Z_G := \{\} \). If there is no finite upper bound on such numbers, then define \( Z_G := -\infty \).

Lemma 7.16. Let \( G \) be the largest nonnegative integer \( m \) such that there exist a strongly connected component \( K \) of \( G \) that is a whirl, a block \( B \) of \( K \), vertices \( u \) and \( w \) in \( B \) and a walk \( u \to v_0 \to v_1 \to \cdots \to v_m \) but \((w, v_0) \notin E(G)\).

Definition 7.17. For a digraph \( G \), let \( \delta(G) \) be the largest nonnegative integer \( m \) such that there exist a strongly connected component \( K \) of \( G \) that is a whirl, a block \( B \) of \( K \), vertices \( u \) and \( w \) in \( B \) and a walk \( u \to v_0 \to v_1 \to \cdots \to v_m \) but \((w, v_0) \notin E(G)\). If there is no finite upper bound on such numbers, then define \( \delta(G) := -\infty \).

Definition 7.18. In the graph \( G \) of Figure II the path \( b_0 \to b_1 \to b_2 \) and the edges \( b_2 \to v \) and \( b_2 \to v' \) witness that \( B_G = 2 \).

Lemma 7.19. Let \( t, t' \in B_n \), \( t \neq t' \), and let \( G \) be a digraph such that \( \delta(G) \) satisfies the identity \( t \approx t' \). Denote \( L := L_{t, t'} \). If \( v_0 \to v_1 \to \cdots \to v_L \) is a
walk and \( v_L \rightarrow v'_L + 1 \) is an edge in \( G \) such that \( v_{L+1} \) and \( v'_{L+1} \) belong to nontrivial strongly connected components \( K \) and \( K' \), respectively, then \( K = K' \). Consequently, \( B_G < L_{t,t'} \).

**Proof.** Denote \( H := H_{t,t'}, \ L := L_{t,t'} \). Using the given walks and vertices of \( K \) and \( K' \), we can build walks \( v_0 \rightarrow \cdots \rightarrow v_H \) and \( v_L \rightarrow v'_L + 1 \rightarrow \cdots \rightarrow v'_{H} \). By Lemma 7.20 \( v_{L+1} \) and \( v'_{L+1} \) belong to the same strongly connected component, i.e., \( K = K' \). \( \square \)

**Definition 7.20.** Let \( t,t' \in B_n, t \neq t' \), and denote \( T := G(t), T' := G(t') \). Let

\[
\Delta_{t,t'} := \{ x \in X_n \ | \ T_x \neq T'_x \},
\]

\[
\Omega_{t,t'} := \{ (d_T(x), h(T_x)), (d_{T'}(x), h(T'_x)) \ | \ x \in \Delta_{t,t'} \},
\]

\[
\xi_{t,t'} := \min \{ d + h \ | \ (d, h) \in \Omega_{t,t'} \},
\]

and define the map \( \omega_{t,t'} : \mathbb{N} \rightarrow \mathbb{N} \) by the rule

\[
\omega_{t,t'}(r) := \begin{cases} 
\min \{ d + h \ | \ (d, h) \in \Omega_{t,t'} \text{ and } d \leq r \}, & \text{if } r < \xi_{t,t'}, \\
\xi_{t,t'}, & \text{if } r \geq \xi_{t,t'}. 
\end{cases}
\]

Note that \( \omega_{t,t'}(0) = H_{t,t'} \) and \( \omega_{t,t'}(r) > L_{t,t'} \) for all \( r \in \mathbb{N} \). Moreover, \( \omega_{t,t'} \) is a nonincreasing function, and we may specify \( \omega_{t,t'} \) by writing down the first few values of \( \omega_{t,t'} \) until \( \xi_{t,t'} \) is reached.

**Example 7.21.** Figure [3] shows two DFS trees corresponding to certain terms \( t,t' \in B_2 \). Note that \( L_{t,t'} = 2 \). It is easy to verify that

\[
\Delta_{t,t'} = \{ x_1, x_2, x_3, x_4, x_5, x_7, x_8, x_9, x_{10}, x_{11}, x_{16}, x_{17}, x_{18} \},
\]

\[
\Omega_{t,t'} = \{ (0,7), (0,6), (1,3), (1,4), (2,2), (2,3), (3,1), (3,2), (4,0), (4,1), (1,6), (1,5), (2,5), (2,4), (3,4), (3,3), (4,3), (4,2), (5,2), (5,0), (2,3), (2,2), (3,0), (3,1), (3,2), (4,0) \},
\]

\[
\xi_{t,t'} = 3,
\]

whence \( \omega_{t,t'} : \mathbb{N} \rightarrow \mathbb{N} \) is the map \( 0 \mapsto 6, 1 \mapsto 4, 2 \mapsto 4, i \mapsto 3 \) for \( i \geq 3 \), or, using the shorthand, \( \omega_{t,t'} = (6,4,4,3, \ldots) \).

**Definition 7.22.** Let \( G \) be a digraph. For \( \ell, r \in \mathbb{N} \) with \( \ell \geq r \geq 1 \), let \( \omega_G(\ell, r) \) be the largest integer \( m \) such that there exist a walk \( v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_\ell \), where \( v_\ell \) belongs to a nontrivial strongly connected component, and a walk \( v_\ell \rightarrow v'_{\ell} \rightarrow v'_{\ell+1} \rightarrow \cdots \rightarrow v'_m \) such that \( v'_m \) belongs to a trivial strongly connected component. If there is no finite upper bound on such numbers \( m \), then define \( \omega_G(\ell, r) := \infty \). If no such number \( m \) exists, then define \( \omega_G(\ell, r) := -\infty \). Note that \( \omega_G(\ell, r) \geq \ell + O_G - 1 \) whenever \( O_G \geq 1 \) (if \( o_0 \rightarrow o_1 \rightarrow \cdots \rightarrow o_{O_G} \) is an outlet of length \( O_G \geq 1 \), then consider a walk \( v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_\ell \) going around the strongly connected component of \( o_0 \) so that \( v_\ell = o_0 \) and the walk \( v_{\ell-1} \rightarrow \cdots \rightarrow v_{L-1} \rightarrow o_1 \rightarrow \cdots \rightarrow o_{O_G} \).

**Example 7.23.** It is not difficult to verify that for the graph \( G \) of Figure [1], the parameter \( \omega_G(\ell, r) \) has the value presented in the table in Figure [1] For the values not shown in the table, that is, for \( \ell, r \in \mathbb{N} \) such that \( \ell \geq 6 \) and \( \ell \geq r \geq 1 \), it holds that \( \omega_G(\ell, r) = \ell + 2 \).
Lemma 7.24. Let \( t, t' \in B_n, t \neq t' \), and let \( G \) be a digraph such that \( h(G) \) satisfies the identity \( t \approx t' \). Denote \( L := L_{t,t'}, \omega := \omega_{t,t'} \). If \( v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_{L+1} \) is a walk in \( G \) such that \( v_{L+1} \) belongs to a nontrivial strongly connected component, \( r \in \{1, \ldots , L+1\} \), and \( v_{r-1} \rightarrow v'_r \rightarrow v'_{r+1} \rightarrow \cdots \rightarrow v'_{\omega(r)} \) is a walk in \( G \) (recall that \( \omega(r) \geq L+1 \)), then \( v'_{L+1} \) belongs to a nontrivial strongly connected component. Consequently, \( \omega_{L_{t,t'},1}(r) < \omega_{t,t'}(r) \) for all \( r \in \{1, \ldots , L_{t,t'}, L+1\} \).

Proof. Denote \( H := H_{t,t'}, M := M_{t,t'}, L := L_{t,t'}, \omega := \omega_{t,t'} \). Let \( K \) be the strongly connected component of \( v_{L+1} \). By Lemma 4.8, \( K \) is an \( m \)-whirl for some divisor \( m \) of \( M \). Let \( B_a \) be the block of \( K \) containing \( v_{L+1} \), and let \( B_{a-1} \) be the predecessor block of \( B_a \).

If \( \omega(r) \geq H \), then the claim follows immediately from Lemma 4.4. We can thus assume that \( \omega(r) < H \). By the definition of \( \omega(r) \) and \( \Omega_{t,t'} \), there exists a vertex \( x_d \in X_n \) such that \( T_{x_d} \neq T'_{x_d} \), and either \( d_T(x_d) \leq r \) and \( d_T(x_d) + h(T_{x_d}) = \omega(r) \) or \( d_T(x_d) \geq r \) and \( d_T(x_d) + h(T_{x_d}) = \omega(r) \); moreover, for all \( x_i \in X_n \) such that \( T_{x_i} \neq T'_{x_i} \), it holds that \( d_T(x_i) \leq r \) implies \( d_T(x_i) + h(T_{x_i}) \geq \omega(r) \), and \( d_T(x_i) \geq r \) implies \( d_T(x_i) + h(T_{x_i}) \geq \omega(r) \). We may assume, by changing the roles of \( t \) and \( t' \) if necessary, that \( d_T(x_d) \leq r \) and \( d_T(x_d) + h(T_{x_d}) = \omega(r) \). Note that if \( d_T(x_d) \leq L \) or \( d_T(x_d) \leq L \), then, by the definition of \( L \), we have \( d_T(x_d) = d_T(x_d) \). Since \( d_T(x_d) \leq r \leq L+1 \), it follows from our assumptions that either \( d_T(x_d) = d_T(x_d) \leq L+1 \) and \( h(T_{x_d}) \leq h(T_{x_d}) \), or \( d_T(x_d) = L+1 < d_T(x_d) \).

We are going to make use of the homomorphism \( \varphi : T \rightarrow G \) that is defined as follows. Fix an \( m \)-cycle \( C \) in \( K \) that contains the vertex \( v_{L+1} \), and let \( W \) be a walk that starts with \( v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_{L+1} \) and continues around \( C \) until it reaches length \( h(T) \). Let \( W' \) be the walk \( v_{d_T(x_d)} \rightarrow v_{r-1} \rightarrow v'_{r} \rightarrow v'_{r+1} \rightarrow \cdots \rightarrow v'_{\omega(r)} \) if \( d_T(x_d) < r \) and \( v'_r \rightarrow v'_{r+1} \rightarrow \cdots \rightarrow v'_{\omega(r)} \) if \( d_T(x_d) = r \). Note that \( W' \) has length exactly \( h(T_{x_d}) \) because \( d_T(x_d) + h(T_{x_d}) = \omega(r) \). Let \( \varphi : X_n \rightarrow V(G) \) be the collapsing map of \((T, x_d)\) on \((W, W')\). By Proposition 2.1, \( \varphi \) is also a homomorphism of \( T' \) into \( G \).

We have \( V(T_{x_d}) = X_{[d,e]} \) and \( V(T'_{x_d}) = X_{[d,e']} \) for some \( e, e' \in [n] \). Consequently \( V(T_{x_d}) \leq V(T'_{x_d}) \) (if \( e \leq e' \)) or \( V(T_{x_d}) \leq V(T'_{x_d}) \) (if \( e' \leq e \)). We will consider several cases and subcases.

Case 1: \( V(T_{x_d}) \subseteq V(T'_{x_d}) \), i.e., \( e < e' \). Then necessarily \( r = d_T(x_d) = L+1 \) and \( x_{e+1} \in V(T'_{x_d}) \setminus V(T_{x_d}) \); note that \( W' \) is the walk \( v'_{L+1} \rightarrow \cdots \rightarrow v'_{\omega(r)} \). Let \( x_p \) be the parent of \( x_{e+1} \) in \( T' \). Then \( d \leq p < e+1 \), so \( x_p \in V(T_{x_d}) \). Moreover, since \( x_{e+1} \) has different parents in \( T \) and \( T' \), we must have \( d_T(x_{e+1}) \geq L+1 \) by the definition
of $L$. Since $\varphi: T' \to G$ is a homomorphism, we have $(\varphi(x_p), \varphi(x_{e+1})) \in E(G)$. Since $x_p \in V(T_{x_d})$, we have $\varphi(x_p) \in \{v'_r, v'_{r+1}, \ldots, v'_{w(r)}\}$; since $x_e \notin V(T_{x_d})$ and $d_T(x_{e+1}) \geq L + 1$, we have $\varphi(x_{e+1}) \in K$. Now we can extend the walk $v_0 \to \cdots \to v_r \to v_{L+1} \to \cdots \to \varphi(x_p) \to \varphi(x_{e+1})$ with vertices of $K$ so that we obtain a walk of length $H$, and Lemma 4.4 implies that $v'_{L+1}$ belongs to a nontrivial strongly connected component, in fact, to $K$ by Lemma 4.9.

Case 2: $V(T_{x_d}) \supseteq V(T_{x_d}')$, i.e., $e \geq e'$. Then $\varphi$ maps $V(T_{x_d})$ on $W'$. Case 2.1: $h(T_{x_d}) < h(T_{x_d}') = h'$. Let $x_d = u_0, u_1, \ldots, u_h'$ be a longest path in $T_{x_d}'$. Write $d_i := d_T(u_i)$ for $i \in \{0, \ldots, h'\}$. Since $h(T_{x_d}) < h(T_{x_d}')$, the sequence $d_0, d_1, \ldots, d_{h'}$ cannot be strictly increasing, so there is an index $i \in \{0, \ldots, h' - 1\}$ such that $d_i \geq d_{i+1}$; in fact, $d_{i+1} \geq L + 1$ by the definition of $L$. Then $(\varphi(u_i), \varphi(u_{i+1})) = (v'_{d_i}, v'_{d_{i+1}}) \in E(G)$, so $v'_{d_{i+1}} \to \cdots \to v'_{d_i} \to v'_{d_i}$ is a closed walk in $G$. It then follows easily from Lemma 4.4 that $v'_{L+1}$ belongs to a nontrivial strongly connected component.

Case 2.2: $h(T_{x_d}) \geq h(T_{x_d}')$. Recall that either $d_T(x_d) = d_T(x_d) \leq L + 1$ and $h(T_{x_d}) \leq h'(T_{x_d}')$, or $d_T(x_d) = L + 1 < d_T(x_d)$. We consider separately these two cases.

Case 2.2.1: $d_T(x_d) = d_T(x_d) \leq L + 1$ and $h(T_{x_d}) \leq h'(T_{x_d}')$. It follows from our assumptions that $h(T_{x_d}) = h'(T_{x_d}')$. If $V(T_{x_d}) \supseteq V(T_{x_d}')$, then we can repeat the above argument with the roles of $t$ and $t'$ switched, and we will reach Case 1 and we are done. We can now assume that $V(T_{x_d}) = V(T_{x_d}')$ (note that this holds if $d_T(x_d) = d_T(x_d) \leq L$). Observe that now the roles of $t$ and $t'$ are symmetric; we would reach this point in the argument even if $t$ and $t'$ were switched, and we may swap them if necessary.

Since $T_{x_d} \neq T_{x_d}'$, there exists an element $x_q \in V(T_{x_d})$ such that $d_T(x_q) \neq d_T'(x_q); assume that the index $q$ is the smallest possible. Swapping the roles of $t$ and $t'$, if necessary, we may assume that $d_T(x_q) < d_T(x_q)$; moreover $d_T(x_q) \geq L + 1$ by the definition of $L$. Let $x_p$ be the parent of $x_q$ in $T'$. Then $p < q$, so by the choice of $x_q$, we have $d_T(x_p) = d_T(x_p) = d_T(x_q) - 1 \geq d_T(x_q) \geq L + 1$. Since $\varphi: T' \to G$ is a homomorphism, we have $(\varphi(x_p), \varphi(x_q)) = (v'_{d_p}, v'_{d_q}) \in E(G)$, where $d_p := d_T(x_p)$, $d_q := d_T(x_q)$. Then $v'_{d_q} \to \cdots \to v'_{d_p} \to v'_{d_q}$ is a closed walk in $G$. It then follows easily from Lemma 4.4 that $v'_{L+1}$ belongs to a nontrivial strongly connected component.

Case 2.2.2: $d_T(x_d) = L + 1 < d_T'(x_d)$. Since $1 \leq r \leq L + 1$ and $d_T(x_d) \leq r$, we have $r = L + 1$ in this case; therefore $W'$ is the walk $v'_{L+1} \to \cdots \to v'_{w(r)}$. Let $x_p$ be the parent of $x_d$ in $T'$. Then $p < d$, so $x_p \notin V(T_{x_d}')$, and $d_T(x_p) \equiv d_T'(x_d) = d_T(x_d) - 1 \equiv d_T(x_d) - 1 = L \pmod{M}$. Moreover, $d_T(x_p) \geq L + 1$, so also $d_T'(x_p) \geq L + 1$ by the definition of $L$, and we have $w := \varphi(x_p) \in B_{q-1}$. Since $\varphi: T' \to G$ is a homomorphism, we have $(\varphi(x_p), \varphi(x_d)) = (w, v'_{L+1}) \in E(G)$.

Define homomorphisms $\psi: T \to G$ and $\psi': T' \to G$ as follows. Let $\psi$ be the collapsing map of $(T, x_d)$ on $(C, W')$ that maps the parent of $x_d$ in $T$ to $w$, and let $\psi'$ be the collapsing map of $(T', x_d)$ on $(C, W')$ that maps the parent of $x_d$ in $T'$ to $w$.

Recall that we are assuming that $V(T_{x_d}) \supseteq V(T_{x_d}')$ and $h(T_{x_d}) \geq h(T_{x_d}')$. If $V(T_{x_d}) \supseteq V(T_{x_d}')$, then using a similar argument as in Case 1 with the homomorphism $\psi'$ in place of $\varphi$, we can find an edge from $W'$ to $K$, from which it follows that $v'_{L+1}$ belongs to a nontrivial strongly connected component. We can thus assume that $V(T_{x_d}) = V(T_{x_d}')$. If $h(T_{x_d}) > h(T_{x_d}')$, then using a similar argument as in Case 2.1 with the homomorphism $\psi'$ in place of $\varphi$, we can find a closed walk in $W'$, from which it follows that $v'_{L+1}$ belongs to a nontrivial strongly connected component. We can thus assume that $h(T_{x_d}) = h(T_{x_d}')$. Now, using a similar argument as in Case 2.2.1 with the homomorphism $\psi$ or $\psi'$ in place of $\varphi$, we can find a closed
walk in $W'$, from which it again follows that $v'_{L+1}$ belongs to a nontrivial strongly connected component.

**Definition 7.25.** Let $t, t' \in B_n$, $t \neq t'$, and denote $T := G(t)$, $T' := G(t')$. Let

$$
\Lambda_{t,t'} := \{ x \in X_n \mid d_T(x) \neq d_{T'}(x), L_{t,t'} + 1 \in \{d_T(x), d_{T'}(x)\}\},
$$

and let

$$
\lambda_{t,t'} := \min\{\max(h(T_x), h(T'_{x'})) \mid x \in \Lambda_{t,t'}\}.
$$

Note that $\Lambda_{t,t'} \neq \emptyset$ by the definition of $L_{t,t'}$; hence $\lambda_{t,t'}$ is well defined and $\lambda_{t,t'} \geq 0$.

**Example 7.26.** For the DFS trees of Figure 3 it holds that

$$
\Lambda_{t,t'} = \{x_{14}, x_{18}, x_{19}\},
$$

$$
\lambda_{t,t'} = \min\{\max(1,1), \max(2,0), \max(1,1)\} = \min\{1, 2, 1\} = 1.
$$

**Definition 7.27.** Let $G$ be a digraph. Let $\lambda_G$ be the largest integer $m$ such that there exist an entryway $u_0 \rightarrow u_1 \rightarrow \cdots \rightarrow u_{E_G}$ (of maximal length $E_G$) to a nontrivial strongly connected component $K$, a vertex $w$ in $K$ with $w \rightarrow u_{E_G}$ and a walk $v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_m$ such that exactly one of the pairs $(w, v_0)$ and $(u_{E_G} - 1, v_0)$ is an edge and the other is not. If there is no upper bound for such numbers $m$, then define $\lambda_G := \infty$. If no such number $m$ exists (this holds in particular when $E_G \leq 0$), then define $\lambda_G := -\infty$.

**Example 7.28.** In the graph $G$ of Figure 1 the longest entryway $e_0 \rightarrow e_1 \rightarrow e_2 \rightarrow e_3 \rightarrow e_4$, the path $\lambda_0 \rightarrow \lambda_1$, the edges $v \rightarrow e_4$ and $v \rightarrow \lambda_0$ and the nonedge $(e_3, \lambda_0)$ witness that $\lambda_G = 1$.

**Lemma 7.29.** Let $t, t' \in B_n$, $t \neq t'$, and let $G$ be a digraph such that $h(G)$ satisfies the identity $t \equiv t'$. Denote $L := L_{t,t'}$, $\lambda := \lambda_{t,t'}$. Assume that $E_G = L + 1$, $u_0 \rightarrow u_1 \rightarrow \cdots \rightarrow u_L \rightarrow u_{L+1}$ is an entryway to a nontrivial strongly connected component $K$, $w$ is a vertex in $K$ with $w \rightarrow u_{L+1}$, and $v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_\lambda$ is a walk in $G$. Then $w \rightarrow v_0$ is an edge if and only if $u_L \rightarrow v_0$ is an edge. (See Figure 3.) Consequently, $\lambda_G < \lambda_{t,t'}$.

**Proof.** Denote $M := M_{t,t'}$, $L := L_{t,t'}$, $\lambda := \lambda_{t,t'}$. By the definition of $\lambda$, there exists an element $x_d \in X_n$ such that $L + 1 \in \{d_T(x_d), d_{T'}(x_d)\}$, $d_T(x_d) \neq d_{T'}(x_d)$, and $\max(h(T_{x_d}), h(T'_{x_d})) = \lambda$. By changing the roles of $t$ and $t'$ if necessary, we may assume that $d_T(x_d) = L + 1 < d_{T'}(x_d)$. Let $x_p$ and $x_q$ be the parents of $x_d$ in $T$ and $T'$, respectively. Then $d_T(x_p) = d_T(x_d) - 1 \equiv L$, $d_T(x_q) = d_T(x_d) - 1 \equiv L + 1$ and $d_{T'}(x_q) = d_{T'}(x_d) - 1 \equiv d_T(x_d) - 1 \equiv L \pmod{M}$.
Denote by \( W \) the entryway \( u_0 \to u_1 \to \cdots \to u_L \to u_{L+1} \) and by \( W' \) the walk \( v_0 \to v_1 \to \cdots \to v_\lambda \). By Lemma 4.8, \( K \) is an \( m \)-whirl for some divisor \( m \) of \( M \). Let \( C \) be an \( m \)-cycle in \( K \) that includes the vertices \( w \) and \( u_{L+1} \).

If \((u_L,v_0) \in E(G)\), then let \( W' \) be the walk that extends \( W \) with vertices of \( C \) to a walk of length \( h(T) \), and consider the collapsing map \( \varphi: X_n \to V(G) \) of \((T,x_d)\) to \((W',W')\). Observe that \( \varphi(x_q) = w \). (In order to see this, we need to verify that \( x_q \notin T_{x_d} \), \( d_T(x_q) \geq L + 1 \) and \( d_T(x_q) \equiv L \) \((\text{mod} \ m)\). The condition \( x_q \notin T_{x_d} \) holds because \( q < d \), as \( x_q \) is the parent of \( x_d \) in \( T' \). If \( d_T(x_q) \leq L \), then \( d_T(x_q) = d_T(x_q) \) by the definition of \( L \); hence \( d_T(x_q) \leq L \), which is a contradiction because we have seen that \( d_T(x_q) \geq L + 1 \). We have also seen that \( d_T(x_q) \equiv L \) \((\text{mod} \ m)\), and \( d_T(x_q) \equiv d_T(x_q) \) \((\text{mod} \ M)\) by the definition of \( M \). These imply \( d_T(x_q) \leq L \) \((\text{mod} \ m)\), and then \( d_T(x_q) \equiv L \) \((\text{mod} \ m)\) follows, as \( m \mid M \). By Proposition 2.1, \( \varphi \) is a homomorphism \( T' \to G \), so \((\varphi(x_q),\varphi(x_d)) = (w,v_0) \in E(G)\).

Remark 7.30. Note that the walk \( v_0 \to v_1 \to \cdots \to v_\lambda \) in Lemma 4.8 may include vertices in the nontrivial strongly connected component \( K \). In particular, Lemma 4.8 asserts that if \( G \) satisfies \( t \approx t' \), \( L := L_{t,t'} \), \( E_G = L + 1 \), and \( u_0 \to u_1 \to \cdots \to u_L \to u_{L+1} \) is an entryway, then there is an edge \( u_l \to v \) for every vertex \( v \) in the block \( B \) of \( u_{L+1} \) in \( K \). This follows by choosing any vertex \( w \) from the predecessor block of \( B \) and taking \( v_0 \to v_1 \to \cdots \to v_\lambda \) to be any walk starting at \( v \) and going around \( K \) until it reaches length \( \lambda \).

We have established above several necessary conditions for a digraph to satisfy a bracketing identity. We show next that these conditions are also sufficient.

Theorem 7.31. Let \( G \) be a digraph, and let \( t,t' \in B_n \) with \( t \neq t' \). Then \( \mathcal{A}(G) \) satisfies the identity \( t \approx t' \) if and only if the following conditions hold:

(i) Every nontrivial strongly connected component of \( G \) is a whirl.

(ii) There is no path from a nontrivial strongly connected component of \( G \) to another.

(iii) \( M_G \subset M_{t,t'} \).

(iv) \( P_G \subset P_{t,t'} \).

(v) \( E_G \subset E_{t,t'} + 1 \).

(vi) \( O_G \subset O_{t,t'} + 1 \).

(vii) \( Z_G \subset Z_{t,t'} \).

(viii) \( B_G \subset B_{t,t'} \).

(ix) \( \omega_G(L_{t,t'} + 1,r) < \omega_{t,t'}(r) \) for all \( r \in \{1, \ldots, L_{t,t'} + 1\} \).

(x) If \( E_G = L_{t,t'} + 1 \), then \( \lambda_G < \lambda_{t,t'} \).

Proof. Denote \( T := G(t) \), \( T' := G(t') \), \( H := H_{t,t'} \), \( M := M_{t,t'} \), \( L := L_{t,t'} \), \( Y := Y_{t,t'} \), \( Z := Z_{t,t'} \), \( \omega := \omega_{t,t'} \), \( \lambda := \lambda_{t,t'} \). The necessity of the conditions is established in Lemmata 4.9, 4.10, 4.19, 4.24.

For sufficiency, assume that the digraph \( G = (V,E) \) and the bracketings \( t,t' \in B_n \) satisfy the conditions. In order to show that \( \mathcal{A}(G) \) satisfies the identity \( t \approx t' \), it suffices, by Proposition 2.1, to show that a map \( \varphi: X_n \to V \) is a homomorphism of \( T \) into \( G \) if and only if it is a homomorphism of \( T' \) into \( G \). So, assume that \( \varphi: X_n \to V \) is a homomorphism of \( T \) into \( G \). We need to verify that \( \varphi \) is a homomorphism of \( T' \) into \( G \).
The image of any path in $T$ under $\varphi$ is a walk in $G$. By conditions (ii), (v) and (vi) it is either a pleasant path, or it comprises an entryway (of length at most $L+1$, possibly 0) to a nontrivial strongly connected component $K$, followed by a winding walk in $K$, again followed by an outlet from $K$ (of length at most $Y+1$, possibly 0). Since $T$ contains a path of length $h(T) \geq H$, condition (iv) implies that the image of $\varphi$ contains a vertex belonging to a nontrivial strongly connected component of $G$.

Our goal is to show that for any edge $(a,b)$ of $T'$, its image $(\varphi(a), \varphi(b))$ is an edge of $G$. Since $T$ and $T'$ are identical up to level $L$, it holds that if $(a,b)$ is an edge of $T'$ with $d_{T'}(a) < L$, then $(a,b)$ is also an edge of $T$ and hence $(\varphi(a), \varphi(b)) \in E(G)$. Therefore we can focus on edges $(a,b) \in E(T')$ with $d_{T'}(a) \geq L$.

Let $x_\ell \in X_\ell$ be an arbitrary vertex with $d_{T'}(x_\ell) = L$. Then also $d_T(x_\ell) = L$ and $V(T_{x_\ell}) = V(T'_{x_\ell}) = X_{\ell,\ell'}$ for some $\ell' \geq \ell$. We will be done if we show that $(\varphi(a), \varphi(b)) \in E(G)$ holds for every edge $(a,b)$ of the rooted induced subtree $T'_{x_\ell}$. The remainder of the proof is a case analysis. The first case distinction is made according to which vertices of $T_{x_\ell}$, if any, are mapped to nontrivial strongly connected components. Each case leads to several subcases. Figure 5 illustrates several main cases and subcases, showing relevant parts of the tree $T$ and highlighting vertices that are mapped to nontrivial strongly connected components.

Case 1: Assume that $\varphi$ maps no vertex of $T_{x_\ell}$ to a nontrivial strongly connected component of $G$. Let $x_1 = u_0 \rightarrow u_1 \rightarrow \cdots \rightarrow u_L = x_\ell$ be the path from $x_1$ to $x_\ell$ in $T'$ (equivalently, in $T$). We make a further case distinction on whether any vertex on this path is mapped to a nontrivial strongly connected component.

Case 1.1: Assume that there is an index $i \in \{0, \ldots, L-1\}$ such that $\varphi(u_i)$ lies in a nontrivial strongly connected component of $G$. It follows from condition (vi) that $h(T_{x_\ell}) \leq Y$; hence $T_{x_\ell} = T'_{x_i}$ by the definition of $Y$. Therefore $(\varphi(a), \varphi(b))$ is clearly an edge of $G$ for every edge $(a,b)$ of $T'_{x_i}$.
Case 1.2: Assume that for all $i \in \{0, \ldots, L - 1\}$, $\varphi(u_i)$ belongs to a trivial strongly connected component. Since the image of $\varphi$ contains a vertex belonging to a nontrivial strongly connected component of $G$, there exists an index $j \in \{0, \ldots, L - 1\}$ such that $T_{u_j}$ contains a vertex that is mapped by $\varphi$ to a nontrivial strongly connected component (at least $T_{x_i} = T_{u_0}$ satisfies this). Assume that $j$ is the largest such index. By condition (vii), $T_{u_j}$ contains a vertex $w$ such that $\varphi(w)$ is in a nontrivial strongly connected component $K$ and $c := d_T(w) \leq L + 1$. Let $x_1 =: v_0 \to v_1 \to \cdots \to v_c$ be the path from $x_1$ to $w$ in $T$; note that $v_i = u_i$ for all $i \leq j$. Then $\varphi(v_0) \to \varphi(v_1) \to \cdots \to \varphi(v_c)$ is a walk in $G$. Continuing this in a suitable way with vertices from $K$, we obtain a walk of length $L + 1$ in $G$, the last vertex of which belongs to $K$. Let then $y$ be a vertex of maximum depth in $T_{u_{j+1}}$, let $d := d_T(y)$, and consider the path $u_0 \to u_1 \to \cdots \to u_{d-1} \to u_d$ from $x_1$ to $y$ in $T$. By the choice of $j$, the walk $\varphi(u_0) \to \varphi(u_1) \to \cdots \to \varphi(u_{d+1}) \to \varphi(u'_{d+2}) \to \cdots \to \varphi(u'_d)$ is pleasant. It follows from condition (ix) that $d < \omega(j + 1)$. By the definition of $\omega$ and $T_{u_j}$, we have $T_{u_{j+1}} = T'_{x_{j+1}}$ and hence $T_{x_i} = T'_{x_i}$, and it follows that $(\varphi(a), \varphi(b)) \in E(G)$ for every edge $(a, b)$ of $T'_{x_i}$.

Case 2: Assume that $\varphi(x_i)$ belongs to a nontrivial strongly connected component $K$. By conditions (ii) and (iii), $K$ is an $m$-whirl for a divisor $m$ of $M$. By condition (ii), $\varphi$ maps each vertex of $T_{x_i}$ to $K$ or to an outlet from $K$. Let $(a, b)$ be an edge of $T'_{x_i}$. We consider the different cases according to whether $a$ and $b$ are mapped to $K$ or not.

Case 2.1: Assume that $\varphi(a) \notin K$. Then $h_T(a) < O_G \leq Y + 1$ by condition (vii), therefore $T_a = T'_a$ by the definition of $Y$, so $(a, b) \in E(T)$ and hence $(\varphi(a), \varphi(b)) \in E(G)$.

Case 2.2: Assume that $\varphi(a), \varphi(b) \in K$. Since $d_T(a) \equiv d_T(b) = 1 \equiv d_T(b) - 1 \pmod{M}$, the vertices $\varphi(a)$ and $\varphi(b)$ lie in consecutive blocks of the $m$-whirl $K$. Therefore $(\varphi(a), \varphi(b)) \in E(G)$.

Case 2.3: Assume that $\varphi(a) \in K$ and $\varphi(b) \notin K$. Again by condition (vii), we have $h_T(b) < O_G \leq Y + 1$ and therefore $T_b = T'_b$. Let $c$ be the parent of $b$ in $T$; note that $c \in V(T_{x_i})$. If $c = a$, then $(\varphi(a), \varphi(b)) = (\varphi(c), \varphi(b)) \in E(G)$ and we are done. If $c \neq a$, then $h_T(c) \geq Z \geq 0$, so there exists a path $b := v_0 \to v_1 \to \cdots \to v_z$ in $T$. Then $\varphi(c) \to \varphi(b) \to \varphi(v_1) \to \cdots \to \varphi(v_z)$ is a walk in $G$. We must also have $\varphi(c) \in K$. (Suppose, to the contrary, that $\varphi(c) \notin K$. Then $h_T(c) \leq Y$ by condition (vii), hence $T_c = T'_c$ by the definition of $Y$, so $(c, b)$ is an edge of both $T$ and $T'$. This contradicts the fact that $a$ is the unique parent of $b$ in $T'$.) Moreover, $d_T(a) \equiv d_T(a) = d_T(b) - 1 \equiv d_T(b) - 1 \equiv d_T(c) \pmod{M}$. Therefore $\varphi(a)$ and $\varphi(c)$ belong to the same block of the $m$-whirl $K$, and it now follows from condition (vii) that $(\varphi(a), \varphi(b)) \in E(G)$.

Case 3: Assume that $\varphi$ maps some vertices of $T_{x_i}$ to nontrivial strongly connected components of $G$ but $\varphi(x_i)$ belongs to a trivial strongly connected component. If $v$ is a vertex of $T_{x_i}$ such that $\varphi(v) \in K$, where $K$ is a nontrivial strongly connected component, and $x_1 := u_0 \to u_1 \to \cdots \to u_L \to \cdots \to u_2 := v$ is the path from $x_1$ to $v$ in $T$, then $\varphi(u_i) \in K$ for all $i \in \{L + 1, \ldots, q\}$ by conditions (ii) and (v). Together with condition (viii), this implies that if $v$ and $v'$ are vertices of $T_{x_i}$ such that $\varphi(v') \in K$, $\varphi(v') \in K'$, where $K$ and $K'$ are nontrivial strongly connected components, then $K = K'$. So, let us assume that $K$ is the unique nontrivial strongly connected component with nonempty intersection with $\varphi(V(T_{x_i}))$. By conditions (ii) and (iii), $K$ is an $m$-whirl for a divisor $m$ of $M$. Moreover, $\varphi(u_0) \to \varphi(u_1) \to \cdots \to \varphi(u_{L+1})$ is an entryway of length $L + 1$, so condition (v) implies $E_G = L + 1$. Now condition (x) in turn implies $\lambda_G < \lambda$. 
Let $x_r \in V(T'_{x_r})$ with $d_T(x_r) = L + 1$, i.e., $x_r$ is a child of $x_t$ in $T'$, and let $x_t := v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_z := x_r$ be the path from $x_t$ to $x_r$ in $T$. We are going to show that $(\varphi(x_t), \varphi(x_r)) \in E(G)$ and that $(\varphi(a), \varphi(b)) \in E(G)$ for every edge $(a, b)$ of $T'_y$. Since $x_r$ was chosen arbitrarily among the children of $x_t$, this will cover all edges of $T'_{x_r}$ and we will be done. We consider different possibilities.

Case 3.1: Assume that $\varphi(x_r) \notin K$.

Case 3.1.1: Assume that $\varphi(v_i) \in K$ for some $i \in \{1, \ldots, z - 1\}$. Then necessarily $z > 1$; hence $d_T(x_r) > L + 1$. In particular, $\varphi(v_i) \in K$ by condition (2) and $\varphi(x_t)$ lies on an outlet, so $h(T_{x_t}) \leq Y$ by condition (2). Consequently, $T_{x_t} = T'_{x_t}$ by the definition of $Y$; therefore, $(\varphi(a), \varphi(b)) \in E(G)$ for every edge $(a, b)$ of $T'_{x_t}$. It remains to show that $(\varphi(x_t), \varphi(x_r)) \in E(G)$.

Observe that also $\varphi(v_{z-1}) \in K$. (Suppose, to the contrary, that $\varphi(v_{z-1}) \notin K$. Then a similar argument as above shows that $T_{v_{z-1}} = T'_{v_{z-1}}$. Recall that the parent of $x_t$ in $T'$ is $x_t$. Since $z > 1$, we must have $v_{z-1} \neq x_t$. Consequently, $(v_{z-1}, x_r) \notin E(T'_{v_{z-1}})$, which contradicts the fact that $(v_{z-1}, x_r) \in E(T_{v_{z-1}}) = E(T'_{v_{z-1}})$.)

This means that

$$d_T(v_{z-1}) = d_T(x_r) - 1 \equiv d_T(x_r) - 1 = d_T(v_1) \pmod{M},$$

so $\varphi(v_{z-1})$ and $\varphi(v_1)$ lie on consecutive blocks of $K$. Since $d_T(x_r) = L + 1 < d_T(x_t)$ and $T_{x_t} = T'_{x_t}$, we have $\lambda \leq \max(h(T_{x_t}), h(T'_{x_t})) = h(T_{x_t})$ by the definition of $\lambda$. Therefore there exists a path $x_r \rightarrow y_1 \rightarrow \cdots \rightarrow y_{\lambda}$ in $T$, and its image $\varphi(x_r) \rightarrow \varphi(y_1) \rightarrow \cdots \rightarrow \varphi(y_{\lambda})$ is a walk of length $\lambda$ in $G$. Since $\varphi(x_1) \rightarrow \cdots \rightarrow \varphi(x_t) \rightarrow \varphi(v_1)$ is an entryway of length $L + 1 = E_G$ and we have edges $(\varphi(v_{z-1}), \varphi(v_1)), (\varphi(v_{z-1}), \varphi(x_t)) \in E(G)$, the inequality $\lambda_G < \lambda$ implies $(\varphi(x_t), \varphi(x_r)) \in E(G)$, as desired.

Case 3.1.2: Assume that $\varphi(v_i) \notin K$ for all $i \in \{1, \ldots, z - 1\}$. Then actually $\varphi(x) \notin K$ for every vertex $x \in V(T_{v_1})$ (for, if there were $x \in V(T_{v_1})$ such that $\varphi(x) \in K$, then, since $d_T(v_1) = L + 1 = E_G$, we would have $\varphi(v_1) \in K$, a contradiction.)

There is, however, an edge $(x_t, y)$ in $T$ with $\varphi(y) \in K$, so condition (3) implies that $d_T(v_1) + h(T_{v_1}) \leq \omega_G(L + 1, L + 1) < \omega(L + 1)$ because $d_T(v_1) = L + 1$. It follows from the definition of $\omega(L + 1)$ that $(d_T(v_1), h(T_{v_1})) \notin \Omega_{x_t}$: hence $T_{v_1} = T'_{v_1}$. We have $x_r \in V(T_{v_1})$. The only rooted induced subtrees of $T'_{x_r}$ containing the vertex $x_r$ are $T'_{x_r}$ and $T'_y$; hence $v_1 = x_r$ or $v_1 = x_t$. The case $v_1 = x_r$ is impossible because $v_1$ is the vertex following $x_r$ on the path from $x_t$ to $x_r$ in $T$; therefore $v_1 = x_t$. Then $(\varphi(x_t), \varphi(x_r)) = (\varphi(x_t), \varphi(v_1)) \in E(G)$. Furthermore, $T_{v_1} = T'_{v_1}$ implies that $(\varphi(a), \varphi(b)) \in E(G)$ for every edge $(a, b)$ of $T'_{v_1} = T'_{x_r}$.

Case 3.2: Assume that $\varphi(x_r) \in K$. Then $\varphi(v_i) \in K$ for all $i \in \{1, \ldots, z\}$. We have

$$d_T(x_r) \equiv d_T(x_t) = d_T(x_t) + 1 = d_T(v_1) + 1 = d_T(v_1) \pmod{M},$$

so $\varphi(x_r)$ and $\varphi(v_1)$ are in the same block $B_i$ of $K$. Let $w$ be a vertex in the predecessor block $B_{i-1}$. Then $w \rightarrow \varphi(x_r)$ and $w \rightarrow \varphi(v_1)$ are edges. Since $\varphi(x_1) \rightarrow \cdots \rightarrow \varphi(x_t) \rightarrow \varphi(v_1)$ is an entryway of length $L + 1 = E_G$ and since there certainly exists a walk of length $\lambda$ starting from $\varphi(x_r)$ (just walk along vertices of $K$), the inequality $\lambda_G < \lambda$ implies that $(\varphi(x_r), \varphi(x_r)) \in E(G)$.

We are going to show that $\varphi$ maps $T'_{x_r}$ homomorphically into $G$. We go through the vertices in $T'_{x_r}$ in depth-first-search order, and we show that every edge of $T'_{x_r}$ is mapped to an edge of $G$. As we will see, it suffices to go along each branch of $T'_{x_r}$ only so far until we reach a vertex $v$ such that $\varphi(v) \notin K$; once such a vertex is reached, the induced subtree rooted at $v$ will automatically be mapped homomorphically into $G$. 
So, let \((a, b) \in E(T'_{x_t})\) and assume that we have already shown that every vertex on the path \(x_t \to \cdots \to a\) in \(T'\) is mapped into \(K\) by \(\varphi\) and every edge along this path is mapped to an edge of \(G\). In particular, \(\varphi(a) \in K\). Let \(c\) be the parent of \(b\) in \(T_1\); \((c, b) \in E(T)\). If \(a = c\), then we clearly have \((\varphi(a), \varphi(b)) = (\varphi(c), \varphi(b)) \in E(G)\).

Assume from now on that \(a \neq c\). We need to consider several cases.

Case 3.2.1. Assume that \(\varphi(b) \in K\). Then \(d_{T_1}(a) \equiv d_{T_1}(a) = d_{T_1}(b) - 1 \equiv d_{T_1}(b) - 1\), that is, \(\varphi(a)\) and \(\varphi(b)\) lie in consecutive blocks of \(K\); then clearly \((\varphi(a), \varphi(b)) \in E(G)\).

Case 3.2.2. Assume that \(\varphi(b) \notin K\).

Case 3.2.2.1. Assume that \(\varphi(c) \notin K\). Then \(\varphi(b)\) lies in an outlet, so \(h(T_b) \leq Y\), whence \(T_b = T'_b\). Since \(a \neq c\), we have \(h(T_b) \geq Z \geq 0\) by the definition of \(Z\), so \(G\) has an outlet of length at least \(Z + 1\) starting with \(\varphi(c) \to \varphi(b) \to \cdots\). Moreover, \(d_{T_1}(a) = d_{T_1}(b) - 1 \equiv d_{T_1}(b) - 1 = d_{T_1}(a) \equiv d_{T_1}(a) \pmod{M}\), so \(\varphi(a)\) and \(\varphi(c)\) are in the same block of \(K\). Now it follows from condition (vi) that \((\varphi(a), \varphi(b)) \in E(G)\). From \(T_b = T'_b\) it follows that \(\varphi\) maps all edges of the subtree \(T'_b\) to edges of \(G\).

Case 3.2.2.2. Assume that \(\varphi(c) \in K\). We claim that \(c = x_t\). Suppose, to the contrary, that the path \(x_t := y_0 \to y_1 \to \cdots \to y_p := c\) from \(x_t\) to \(c\) in \(T\) has length \(p \geq 1\). Then \(\varphi(y_i) \notin K\) for all \(i \in \{0, 1, \ldots, p\}\) (otherwise \(\varphi(c)\) would lie in an outlet, so \(h(T_1) \leq Y\), whence \(T_1 = T'_1\), which is clearly a contradiction since \((c, b)\) is an edge in \(T\) but not in \(T'\)). In fact, \(\varphi(x) \notin K\) for all \(x \in V(T_{y_0})\) by condition (v).

Recall the path \(x_t := v_0 \to v_1 \to \cdots \to v_x := x_t\) in \(T\). Since \(\varphi(x_t) \notin K\), \(\varphi(x_t) \in K\), and \(d_{T_1}(v_1) = L + 1\), condition (vi) implies \(\varphi(v_1) \in K\). Then condition (ix) implies that \(d_{T_1}(y_1) + h(T_{y_1}) \leq \omega_G(L + 1, L + 1) < \omega(L + 1)\); hence \((d_{T_1}(y_1), h(T_{y_1})) \notin \Omega_{t,t'}\), so \(T_{y_1} = T'_{y_1}\). Since \((c, b)\) is an edge in \(T_{y_1}\), this implies that \((c, b)\) is also an edge of \(T'\), a contradiction.

Since \(c = x_t\), we have \(d_{T_1}(b) = L + 1\). Since \(\varphi(b) \notin K\), condition (vi) implies that \(\varphi(x) \notin K\) for all \(x \in V(T_b)\). Using again the fact that \(x_t \to v_1\) is an edge of \(T\), \(\varphi(v_1) \in K\), and \(d_{T_1}(v_1) = L + 1\), condition (ix) implies \(d_{T_1}(b) + h(T_b) \leq \omega_G(L + 1, L + 1) < \omega(L + 1)\); hence \((d_{T_1}(b), h(T_b)) \notin \Omega_{t,t'},\) so \(T_b = T'_b\). On the other hand, \(d_{T_1}(b) > L + 1\). Therefore \(\lambda \leq \max(h(T_b), h(T'_{b})) = h(T_b)\) by the definition of \(\lambda\), so there is a path of length \(\lambda\) starting at \(\varphi(b)\). Furthermore, \(d_{T_1}(a) \equiv d_{T_1}(a) = d_{T_1}(b) - 1 \equiv d_{T_1}(b) - 1 = d_{T_1}(c) = L = d_{T_1}(v_1) - 1 \pmod{M}\), so \(\varphi(a)\) and \(\varphi(v_1)\) lie in consecutive blocks of \(K\), that is, \((c, b) \to (\varphi(a) \to \varphi(v_1))\) is an edge. Now the inequality \(\lambda_G < \lambda\) implies that \((\varphi(a), \varphi(b)) \in E(G)\). From \(T_b = T'_b\) it follows that \(\varphi\) maps all edges of the subtree \(T'_{b}\) to edges of \(G\).

This exhausts all cases, and we conclude that \(\varphi\) is a homomorphism of \(T'\) to \(G\). Switching the roles of \(T\) and \(T'\), the same argument shows that every homomorphism of \(T'\) to \(G\) is a homomorphism of \(T\) to \(G\). Proposition 2.1 now yields \(\mathbb{A}(G) \models t \approx t'\).

\(\square\)

8. Special cases

As an illustration of the parameters and results of the previous section, we now present how some of the main results of Part I can be derived as special cases of Theorem 7.31. When restricted to undirected graphs, Theorem 7.31 is reduced to the following proposition, which together with Lemma 3.1 leads to Theorem 3.3.

**Proposition 8.1.** Let \(G\) be an undirected graph.

(i) If every connected component of \(G\) is either trivial or a complete graph with loops, then \(\mathbb{A}(G)\) satisfies every bracketing identity.

(ii) If every connected component is either trivial, a complete graph with loops, or a complete bipartite graph, and the last case occurs at least once, then \(G\) satisfies a nontrivial bracketing identity for \(t \approx t'\) if and only if \(M_{t,t'}\) is even.

(iii) Otherwise \(G\) satisfies no nontrivial bracketing identity.
Proof. The strongly connected components of an undirected graph are just its connected components, and every symmetric edge is part of a cycle. Therefore, an undirected graph \( G \) has no pleasant path of nonzero length and consequently no entryway nor outlet of nonzero length; thus \( P_G \leq 0 \), \( E_G \leq 0 \), \( O_G \leq 0 \). It also clearly holds that \( B_G = -\infty \), \( \lambda_G = -\infty \), and \( \omega_G(\ell, r) = -\infty \) for all \( \ell, r \in \mathbb{N} \) with \( \ell \geq r \geq 1 \). The only whirls with symmetric edges are 1-whirls (i.e., complete graphs with loops) and 2-whirls (i.e., complete bipartite graphs). From this it also easy to see that \( Z_G = -\infty \).

For this reason, condition \((\text{ii})\) of Theorem 7.31 is automatically satisfied, and conditions \((\text{iv}) - (\text{x})\) obviously hold for any \( t, t' \in B_n \) with \( t \neq t' \), Therefore it is only conditions \((\text{i})\) and \((\text{iii})\) that matter.

Consider first the case that every nontrivial connected component of \( G \) is a 1-whirl. Then \( M_G = 1 \). Since \( 1 \mid M_{t, v} \) for any \( t, t' \in B_n \), \( t \neq t' \), it holds that \( A(G) \) satisfies every bracketing identity.

Consider now the case that every nontrivial connected component of \( G \) is a 1-whirl or a 2-whirl and at least one of the components is a 2-whirl. Then \( M_G = 2 \), so \( A(G) \) satisfies a nontrivial bracketing identity \( t \approx t' \) if and only if both \( 2 \mid M_{t, v} \).

Finally, in the case when \( G \) has a nontrivial connected component that is not a whirl, \( A(G) \) satisfies no nontrivial bracketing identity. \( \square \)

An equivalent characterization of associative digraphs is obtained as a special case of Theorem 7.31.

**Proposition 8.2.** Let \( G \) be a digraph. Then \( A(G) \) satisfies the identity \( x_1(x_2x_3) \approx (x_1x_2)x_3 \) if and only if the nontrivial strongly connected components of \( G \) are complete graphs with loops, and for every vertex \( v \in V(G) \), the outneighbourhood of \( v \) is a nontrivial strongly connected component.

**Proof.** Denote \( t := x_1(x_2x_3) \) and \( t' := (x_1x_2)x_3 \). It is straightforward to verify that this pair of bracketings has the following parameters (see Figure 3 of Part I):

\[
\begin{align*}
H_{t, t'} &= 1, & L_{t, t'} &= 0, & M_{t, t'} &= 1, & Y_{t, t'} &= -1, & Z_{t, t'} &= 0, \\
\Omega_{t, t'} &= \{(0, 2), (0, 1), (1, 1), (1, 0)\}, & \omega_{t, t'} &= (1, 1, \ldots), & \Lambda_{t, t'} &= \{x_3\}, & \lambda_{t, t'} &= 0.
\end{align*}
\]

With these parameters, the conditions of Theorem 7.31 for \( A(G) \) to satisfy the identity \( t \approx t' \) are reduced to the following:

(i) Every nontrivial strongly connected component of \( G \) is a whirl.
(ii) There is no path from a nontrivial strongly connected component of \( G \) to another.
(iii) \( M_G = 1 \).
(iv) \( P_G \leq 0 \).
(v) \( E_G \leq 1 \). (This follows already from \((\text{iv})\))
(vi) \( O_G \leq 0 \).
(vii) \( Z_G = -\infty \). (This is also a consequence of \((\text{i})\) and \((\text{iii})\))
(viii) \( B_G = -\infty \). In view of conditions \((\text{iv})\) and \((\text{vi})\), this means that all outneighbours of a vertex belong to the same nontrivial strongly connected component.
(ix) \( \omega_G(1, 1) = -\infty \). (This is also a consequence of \((\text{iv})\) and \((\text{vi})\))
(x) If \( E_G = 1 \), then \( \lambda_G = -\infty \). This means that for any vertex \( v \) belonging to a trivial strongly connected component, if \( (v, u) \) is an edge, then \( (v, w) \) is an edge for all vertices \( w \) in the strongly connected component of \( u \).

The above conditions are easily seen to be equivalent to the following: the nontrivial strongly connected components of \( G \) are complete graphs with loops, and for
every vertex $v \in V(G)$, the outneighbourhood of $v$ is an entire nontrivial strongly connected component. \hfill \Box

9. Spectrum dichotomy

Theorem 7.31 provides a necessary and sufficient condition for a graph algebra to satisfy a nontrivial bracketing identity. However, the theorem does not directly give information on the number of distinct term operations of a graph algebra induced by the bracketings of a given size. Although a general description of the associative spectra of digraphs still eludes us, we can find some bounds for the possible associative spectra. In fact, as we will see in Theorem 9.5, the associative spectrum of a graph algebra is either constant at most 2 or it grows exponentially.

In preparation for this dichotomy result, we shall determine the associative spectrum of the graph algebra corresponding to a certain graph on three vertices (see Proposition 9.3).

**Lemma 9.1.** For $n \geq 2$ let $R_n$ be the set of words $\rho$ of length $n$ over the alphabet \{0, 1\} that satisfy the following three conditions:

(i) $\rho$ does not start with 01,
(ii) $\rho$ does not end with 10,
(iii) $\rho$ does not contain 101.

Then $|R_n|$ is asymptotically $\Theta(a^n)$, where $a \approx 1.755$ is the unique positive root of the polynomial $x^4 - x^3 - x^2 - 1$.

*Proof.* It is straightforward to verify that the map $\psi$ defined by the following formula is a bijection from $R_{n-1} \cup R_{n-2} \cup R_{n-4}$ to $R_n$ for all $n \geq 6$:

$$\psi(\rho) = \begin{cases} n1, & \text{if } \rho \in R_{n-1}, \\ n00, & \text{if } \rho \in R_{n-2}, \\ n1000, & \text{if } \rho \in R_{n-4}. \end{cases}$$

Thus we have the recurrence relation $|R_n| = |R_{n-1}| + |R_{n-2}| + |R_{n-4}|$. The characteristic polynomial of this linear recurrence is $x^4 - x^3 - x^2 - 1$, and its roots are

$$\alpha \approx 1.755, \quad \beta \approx 0.123 + 0.745i, \quad \gamma \approx 0.123 - 0.745i, \quad \delta = -1.$$ 

Therefore, $|R_n| = a \cdot \alpha^n + b \cdot \beta^n + c \cdot \gamma^n + d \cdot \delta^n$ for suitable complex numbers $a, b, c, d$. Since $\alpha$ is the only characteristic root of absolute value greater than one, the dominant term is $a \cdot \alpha^n$; hence we have $|R_n| = \Theta(a^n)$. \hfill $\Box$

**Remark 9.2.** The sequence of values $|R_n|$ appears as sequence A005251 in the OEIS [5].

**Proposition 9.3.** The associative spectrum $s_n$ of the graph algebra corresponding to the graph $G$ given by $V(G) = \{u, v, w\}$, $E(G) = \{(u, v), (u, w), (v, w)\}$ is $s_n = |R_{n-1}|$ for all $n \geq 3$. Hence $s_n$ is asymptotically $\Theta(\alpha^n)$.

*Proof.* For any DFS tree $T$ of size $n$, a map $\varphi : X_n \to \{u, v, w\}$ is a homomorphism of $T$ into $G$ if and only if either $\varphi(x_1) = w$, or $\varphi(x_1) = u$ and all vertices mapped to $v$ are leaves of depth one in $T$:

$$\forall p \in X_n: \varphi(p) = v \implies d_T(p) = 1 \text{ and } h(T_p) = 0.$$ 

By Proposition 2.1, this implies that $A(G)$ satisfies a bracketing identity $t \approx t'$ if and only if the corresponding DFS trees $G(t)$ and $G(t')$ have the same leaves on level one. Thus $s_n$ counts the number of subsets of $S \subseteq \{x_2, \ldots, x_n\}$ that can occur

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This means that there exist positive constants $c_1, c_2$ such that $c_1 \alpha^n \leq |R_n| \leq c_2 \alpha^n$. 

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[5] The Online Encyclopedia of Integer Sequences.
as the set of “depth-one leaves” of a DFS tree of size $n$. We claim that such sets $S$ are characterized by the following three conditions:

(a) if $x_3 \in S$, then $x_2 \in S$;
(b) if $x_{n-1} \in S$, then $x_n \in S$;
(c) if $x_i, x_{i+2} \in S$, then $x_{i+1} \in S$ for all $2 \leq i \leq n - 2$.

It is clear that these conditions are necessary. Conversely, assume that $S = \{x_i, \ldots, x_k\} \subseteq \{x_2, \ldots, x_n\}$ with $2 \leq i_1 < \cdots < i_k \leq n$ satisfies the three conditions above. Let us construct a DFS tree $T$ of size $n$ as follows. For each $x_i \in S$, let $x_i$ be a child of the root $x_1$, and let $x_{i_k}$ have no children. If $k < s$ and $i_{k+1} > i_k + 1$, then let $x_{i_{k+1}}$ be also a child of $x_1$, and let $x_{i_{k+2}}, \ldots, x_{i_{k+1} - 1}$ be the children of $x_{i_{k+1}}$. Note that condition (c) guarantees that this is a nonempty set of children; hence $x_{i_{k+1}}$ is not a leaf. In addition, if $x_2 \notin S$ (i.e., $i_1 > 2$), then let $x_2$ be a child of $x_1$, and let $x_3, \ldots, x_{i_1 - 1}$ be the children of $x_2$. Again, condition (a) ensures that at least $x_3$ will be a child of $x_2$, hence $x_2$ is not a leaf in this case. Similarly, if $x_n \notin S$ (i.e., $i_k < n$), then let $x_{i_k + 1}$ be a child of $x_1$, and let $x_{i_k + 2}, \ldots, x_n$ be the children of $x_{i_k + 1}$. Condition (b) guarantees that $x_{i_k + 1}$ is not a leaf. This construction yields a DFS tree $T$ whose depth-one leaves are exactly the elements of $S$.

If we encode a set $S \subseteq \{x_2, \ldots, x_n\}$ by a word $\chi \in \{0, 1\}^{n-1}$ in a standard way (i.e., $\chi_i = 1$ if and only if $i + 1 \in S$), then conditions (a)–(c) translate to conditions (i),(ii),(iii) of Lemma 9.1. Then we can conclude that $s_n = |R_n - 1| = \Theta(\alpha^n)$. □

Lemma 9.4. For $n > 1$, the number of DFS trees on $n$ vertices of height at most 2 is $2^{n-2}$.

Proof. The depth sequence of a DFS tree on $n$ vertices of height at most 2 is clearly an element of $\{0\} \times \{1\} \times \{1, 2\}^{n-2}$, because the root $x_1$ is the only vertex at depth 0, $x_2$ must have depth 1, and the remaining vertices may have depth 1 or 2. Conversely, every tuple $(d_1, d_2, \ldots, d_n) \in \{0\} \times \{1\} \times \{1, 2\}^{n-2}$ is a zag sequence and hence a depth sequence of some DFS tree by Proposition 2.6. The claim now follows, since DFS trees are uniquely determined by their depth sequences by Proposition 2.5, and $|\{0\} \times \{1\} \times \{1, 2\}^{n-2}| = 2^{n-2}$. □

Lemma 9.5. Let $\sim$ be the equivalence relation on $B_n$ that relates $t$ and $t'$ if and only if $T := G(t)$ and $T' := G(t')$ coincide up to level one, i.e.,

$$\forall p \in X_n: d_T(p) = 1 \iff d_{T'}(p) = 1.$$ 

Then $|B_n/\sim| = 2^{n-2}$ for $n \geq 2$.

Proof. We need to count sets $S \subseteq \{x_2, \ldots, x_n\}$ that can occur as the set of depth-one vertices of a DFS tree of size $n$. Clearly, $x_2 \in S$ holds for such sets. We claim that this condition is also sufficient. Indeed, let $S = \{x_{i_1}, \ldots, x_{i_k}\} \subseteq \{x_2, \ldots, x_n\}$ with $2 = i_1 < \cdots < i_k \leq n$, and let us construct a DFS tree $T$ as follows. For each $x_i \in S$, let $x_i$ be a child of the root $x_1$, and let $x_{i_k + 1}, \ldots, x_{i_k + 1, s}$ be the children of $x_{i_k}$ (it is possible that this is an empty set of children). Then the depth-one vertices of $T$ are exactly the elements of $S$. We can conclude that $|B_n/\sim|$ is the number of subsets of $\{x_2, \ldots, x_n\}$ that contain $x_2$, and this is obviously $2^{n-2}$. □

By a directed bipartite graph we mean a bipartite graph $G = (V, E)$ with bipartition $V = V_1 \cup V_2$ such that $E \subseteq V_1 \times V_2$ (i.e., all edges go to the “same direction”). The weakly connected components of a digraph $G$ are its induced subgraphs on (the vertex sets of) the connected components of the underlying undirected graph of $G$.

Theorem 9.6. For any digraph $G$ we have the following three mutually exclusive cases.
(i) The associative spectrum of $\mathcal{A}(G)$ is constant 1. These digraphs are characterized in Proposition 4.1 or, equivalently, in Proposition 5.2.

(ii) The associative spectrum of $\mathcal{A}(G)$ is constant 2. This holds if and only if each weakly connected component of $G$ is either associative or a directed bipartite graph with at least one edge, and the latter occurs at least once.

(iii) In all other cases the associative spectrum of $\mathcal{A}(G)$ is bounded below by the spectrum of the graph given in Proposition 7.3, i.e., $s_n(\mathcal{A}(G)) \geq |R_{n-1}| = \Theta(\alpha^n)$ (cf. Lemma 6.7).

Proof. Let $G$ be an arbitrary digraph, and let $s_n = s_n(\mathcal{A}(G))$ denote the associative spectrum and $\sigma_n = \sigma_n(\mathcal{A}(G))$ denote the fine associative spectrum of the corresponding graph algebra. Let us assume that $s_n$ does not grow exponentially. Then $G$ satisfies conditions (i) and (ii) of Theorem 7.31 (otherwise the associative spectrum would consist of the Catalan numbers). If $MG \geq 2$, then $G$ contains an induced subgraph that is isomorphic to the directed cycle $C_n$ for some $n \geq 2$; hence $s_n \geq s_n(C_n) = 2^{n-2}$ by Proposition 5.4 and Remark 5.5, contradicting our assumption on the growth of the spectrum. If $P_G \geq 2$, then condition (iv) of Theorem 7.31 shows that all bracketings corresponding to DFS trees of height at most 2 fall into different equivalence classes of the fine spectrum $\sigma_n$. Therefore, Lemma 9.4 implies that $s_n \geq 2^{n-2}$, a contradiction. If $E_G \geq 2$, then by condition (v) of Theorem 7.31, bracketings $t, t' \in B_n$ fall into different equivalence classes of the fine spectrum whenever the corresponding DFS trees differ at level one. Hence, by Lemma 9.5, we have $s_n \geq 2^{n-2}$, which is a contradiction again. A similar argument using condition (vi) of Theorem 7.31 and Lemma 5.6 shows that $O_G \geq 1$ also leads to the contradiction $s_n \geq 2^{n-2}$.

We have proved thus far that if $\mathcal{A}(G)$ has a subexponential spectrum, then $G$ satisfies conditions (i) and (ii) of Theorem 7.31 and the (in)equalities $MG = 1$, $P_G \leq 1$, $E_G \leq 1$, $O_G \leq 0$. Let us assume that the latter hold, and let $V_0$ be the union of the vertex sets of the nontrivial strongly connected components of $G$ (if there are any). From $P_G \leq 1$, $E_G \leq 1$ and $O_G \leq 0$ we can see that no vertex of $V \setminus V_0$ can have an inneighbour and an outneighbour at the same time. Let $V_1$ be the set of vertices that have an outneighbour, and let $V_2 := V \setminus (V_0 \cup V_1)$. Thus $V = V_0 \cup V_1 \cup V_2$ (some of these sets might be empty), and the subgraph induced on $V_1 \cup V_2$ is a directed bipartite graph, whereas the subgraph induced on $V_0$ is a disjoint union of complete graphs with loops by conditions (i) and (ii) of Theorem 7.31 and by $MG = 1$. Since $O_G \leq 0$, there is no edge from $V_0$ to $V_1 \cup V_2$, and there is no edge from $V_2$ to $V_0$ by the definition of $V_2$, but we may have edges from $V_1$ to $V_0$.

Let $(v_1, v_0)$ be such an edge (i.e., $v_1 \in V_1$ and $v_0 \in V_0$). If $v'_0$ is another vertex in the strongly connected component of $v_0$, then we must have the edge $(v_1, v'_0)$. Indeed, if this was not the case, then subgraph induced on $\{v_1, v_0, v'_0\}$ would be isomorphic to the graph of Proposition 5.9, and it has an exponential spectrum. (Note that the spectrum of any induced subgraph provides a lower estimate of the spectrum of the whole graph.) On the other hand, if $v'_0$ belongs to another nontrivial strongly connected component, then the presence of the edge $(v_1, v'_0)$ would give rise to an induced subgraph isomorphic to that of Proposition 5.8, again contradicting our assumption about the subexponential growth of the spectrum. Thus we have proved that if a vertex of $V_1$ has outneighbours in $V_0$, then these outneighbours form a nontrivial strongly connected component.

Finally, if a vertex $v_1 \in V_1$ has an outneighbour $v_0 \in V_0$ and also an outneighbour $v_2 \in V_2$, then the subgraph induced on $\{v_1, v_2, v_0\}$ is isomorphic to the graph of Proposition 9.3, forcing again an exponential spectrum. Thus some vertices of $V_1$ have outneighbours only in $V_0$, while others have outneighbours only in $V_2$. The
former vertices together with $V_0$ form an associative graph (see Proposition 8.2), while the latter vertices together with $V_2$ form a directed bipartite graph. This proves that every digraph with a subexponential associative spectrum belongs to cases (i) or (ii) of the current theorem.

It only remains to prove that the spectrum of a directed bipartite graph with at least one edge is constant 2. But this is easily done with the help of Theorem 7.31. All conditions except for (iv) are satisfied trivially for all $t, t' \in B_n$ with $t \neq t'$. Condition (iv) gives $1 = P_G < H_{t,t'}$, which means that $\sigma_n$ has two equivalence classes: $\{t\}$ and $B_n \setminus \{t\}$, where $t = ((\cdots((x_1,x_2)\cdots)x_{n-1})x_n$ is the bracketing that corresponds to the unique DFS tree of size $n$ and height 1. □

**Remark 9.7.** Theorem 9.6 implies that there are only two different bounded spectra of graph algebras, namely constant 1 and constant 2. For arbitrary groupoids, all sequences of the form $(2,\ldots,2,1,\ldots)$ can occur as associative spectra, and there are other bounded spectra (e.g., constant 3), too [1]. Theorem 9.6 also implies that unbounded spectra of graph algebras grow exponentially, the smallest growth rate being $\Theta(\alpha^n)$. This is not true for arbitrary groupoids either: there exist groupoids with polynomial spectra of arbitrary degrees [3].

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