

Confluence theory for graphs

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We develop a theory of confluence of graphs. We describe an algorithm for proving that a given system of reduction rules for abstract graphs and graphs in surfaces is locally confluent. We apply this algorithm to show that each simple Lie algebra of rank at most 2, gives rise to a confluent system of reduction rules of graphs (via Kuperberg’s spiders) in an arbitrary surface. As a further consequence of this result, we find canonical bases of SU_3 -skein modules of cylinders over orientable surfaces.

57M15, 57M27; 05C10, 16S15

1 Introduction

This paper is motivated by the following problem appearing in representation theory of Lie algebras and of quantum groups, in the study of moduli spaces, in knot theory, and in other areas of mathematics. We state it first for abstract graphs and, later, for graphs in manifolds.

Let R be a ring. An R -linear graph is a formal R -linear combination of graphs $\Gamma = \sum_{i=1}^k r_i \Gamma_i$, such that the graphs Γ_i have distinguished sets E_i of 1-valent vertices (called *external*) and there are specified bijections $E_1 \simeq E_2 \simeq \cdots \simeq E_k$. For any graph Γ' with a distinguished set of 1-valent external vertices E' in a bijection with E_1 (and, consequently, in a bijection with E_i for all i), let $\langle \Gamma_i, \Gamma' \rangle$ denote the contraction of Γ_i and Γ' along their external vertices, respecting the specified bijections. In the process of the contraction these 1-valent vertices are removed and adjacent edges identified. Finally, let $\langle \Gamma, \Gamma' \rangle = \sum_{i=1}^k r_i \langle \Gamma_i, \Gamma' \rangle$.

Let \mathcal{G} be a set of graphs, $\{\Gamma_i\}_{i \in I}$ be a set of R -linear graphs, and let $\mathcal{R}(\Gamma_i, i \in I) \subset R\mathcal{G}$ be the submodule generated by contractions $\langle \Gamma_i, \Gamma' \rangle$ for all $i \in I$ and all graphs Γ' as above.

- (1) Is $R\mathcal{G}/\mathcal{R}(\Gamma_i, i \in I)$ a free R -module? If so, then find an explicit basis of it.
- (2) Can a basis be given by taking all graphs in \mathcal{G} satisfying a certain “natural” property?

Examples appear in Section 8.

The topological version of this problem in dimension n involves topological graphs embedded in n -dimensional manifolds. An R -linear topological graph is $\Gamma = \sum_i^k r_i \Gamma_i$, such that $\Gamma_1, \dots, \Gamma_k$ lie in a manifold M of dimension n and there is a finite set $E \subset \partial M$, such that $\Gamma_i \cap \partial M = E$ for every i and this set is composed of 1-valent vertices of Γ_i . If $\iota: M \rightarrow N$ is an embedding into a manifold of equal dimension and Γ' is a graph in $\overline{N \setminus \iota(M)}$ such that points of E are 1-valent vertices of Γ' then $\langle \Gamma_i, \Gamma' \rangle$ denotes the contraction of graphs Γ_i and Γ' along the vertices in E . As before, $\langle \Gamma, \Gamma' \rangle = \sum_i r_i \langle \Gamma_i, \Gamma' \rangle$.

Now, let \mathcal{G} be a set of topological graphs in N and Γ_i be an R -linear graph in M_i , for every i in some index set I . As before, let $\mathcal{R}(\Gamma_i, i \in I) \subset R\mathcal{G}$ be the submodule generated by $\langle \Gamma_i, \Gamma' \rangle$ for all i 's and all embeddings $\iota: M_i \rightarrow N$ and all graphs Γ' as above. In this setting we ask again questions (1) and (2) above.

The flavor of these questions depends on the dimension of the manifold N :

Dimension 2 Interesting examples come from Kuperberg's spider webs [36], which provide a convenient graphical description of representation theory of Lie algebras and associated quantum groups of rank ≤ 2 . (Spider webs for $SO(7)$, which has rank 3, were worked out by the second author in [65].) These are spaces of graphs in D^2 considered modulo certain relations, of the type defined above. The classes of graphs considered and the relations between them depend on the Lie algebra in question. Because of their applications to quantum invariants, it is important to consider Kuperberg's webs in surfaces other than D^2 as well. We answer (1) and (2) for these graphs in Sections 4–7. Our approach is based on theory of confluence of graphs developed in Section 2 and an algorithm for finding confluent reduction rules for graphs described in Section 3.6. As an application, we will find canonical bases of skein modules of skein modules of $[0, 1]$ -bundles over surfaces for all simple Lie groups of rank 1 and 2. This reproves a theorem of Przytycki [52, Theorem 3.1] for the Kauffman bracket (SU_2) skein modules of $[0, 1]$ -bundles over surfaces and answers the question for SU_3 -skein modules, cf Frohman–Zhong [18] and Sikora [62].

Dimension 3 The three-dimensional version of this problem appears in knot theory, for example, in connection with Vassiliev invariants and skein modules. In both cases, (1) and (2) are open in general.

Dimension > 3 In dimensions greater than 3 homotopic graphs are isotopic, and therefore the problem of describing $R\mathcal{G}/\mathcal{R}(\Gamma_i, i \in I)$ can be reduced to purely algebraic form depending on $\pi_1(N)$ only, since every $\Gamma \subset N$ is determined by a labeling all cycles of Γ by conjugacy classes of $\pi_1(N)$. In particular, if $\pi_1(N)$ is trivial then

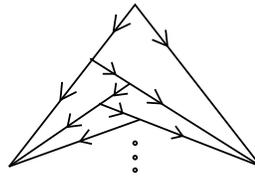


Figure 1

graphs in N can be thought as abstract graphs. For that reason, it is enough to consider questions (1) and (2) for abstract graphs only.

2 Confluence

We will approach the problems outlined in Introduction, by the method of confluence. To introduce it in its most abstract form, consider a set of objects V and a set of reduction rules, E , composed of pairs of elements of V , denoted by $v \rightarrow v'$. In other words, (V, E) is an arbitrary directed graph. A sequence of its vertices $v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_n$ is called a *descending path* and its existence is denoted by $v_1 \xrightarrow{*} v_n$. We say that v_n is a *descendant* of v_1 . We allow the empty path, $v \xrightarrow{*} v$, for any v . Consequently, $v \xrightarrow{*} w$ is a relation on V which is reflexive and transitive but not necessarily symmetric. We write $v \sim w$ if there is a finite path connecting v and w . (The edges of this path may have arbitrary directions.)

The reduction rules E are (*globally*) *confluent* if all $v_1 \sim v_2$ have a common descendant, that is, $w \in V$ such that $v_1 \xrightarrow{*} w$ and $v_2 \xrightarrow{*} w$. Finally, rules E are *locally confluent* if for any v, w_1, w_2 such that $v \rightarrow w_1, v \rightarrow w_2$, the elements w_1, w_2 have a common descendant. Clearly, global confluence implies local confluence. However, the opposite implication fails, as shown in the graph in Figure 1, containing infinitely many vertices and edges.

Nonetheless, under certain mild conditions on reduction rules, local confluence implies global confluence. We say that reduction rules are *terminal* if all descending paths are finite.

Diamond Lemma (Newman [43, Theorem 3]) *If reduction rules are terminal then local confluence implies global confluence.*

An example of an application of the Diamond Lemma is the Jordan-Hölder theorem, which follows directly from this result. Other applications of the Diamond Lemma to ring theory and group theory are discussed by Bergman [4] and Sims [63]. Furthermore,

the Diamond Lemma and the notion of confluence is used in mathematical logic: in Church calculus (see Lalement [37] and Newman [43]), in lambda calculus (see Baader–Nipkow [3], Curien [12], Ohlebusch [45], Lalement [37] and Mitchel [41]), and in equational logic (see O’Donnell [44]). Additionally, it appears in computer science, in the theory of rewriting systems and in the study of graph grammars (see Ehrig [13; 14] and Nagl [42]).

2.1 Confluence of linear objects

For our applications we need a generalization of the notion of confluence to linear objects. For a ring R , an R -linear reduction rule on a set V is a pair $S: v \rightarrow \sum_{i=1}^n r_i v_i$ where $v, v_1, \dots, v_n \in V$ and $r_1, \dots, r_n \in R$. Denote the free R -module over V by RV . For $X, Y \in RV$, we write $X \xrightarrow{S} Y$ if v appears with a non-zero coefficient in X and Y is obtained from X by replacing v by $\sum_{i=1}^n r_i v_i$. Finally, given a family of reduction rules, $\{S_i\}_{i \in I}$, we write $X \xrightarrow{*} Y$ if there is a sequence of reduction rules leading from X to Y . Denote the R -submodule of RV generated by $X - Y$ for all $X \xrightarrow{S_i} Y$ by $\mathcal{R}(S_i, i \in I)$ and write $X_1 \sim X_2$ if $X_1 - X_2 \in \mathcal{R}(S_i, i \in I)$. As before, we say that rules $\{S_i\}_{i \in I}$ are (globally) confluent if any $X_1 \sim X_2$ have a common descendant, that is, there is Y such that $X_1 \xrightarrow{*} Y$ and $X_2 \xrightarrow{*} Y$. Finally, rules $\{S_i\}_{i \in I}$ are locally confluent on V (respectively, on RV) if, for any $X \in V$ (respectively, any $X \in RV$) and any $Y_1, Y_2 \in RV$ such that $X \xrightarrow{S_i} Y_1$, $X \xrightarrow{S_j} Y_2$, Y_1 and Y_2 have a common descendant. Clearly, global confluence implies local confluence on RV , and terminal local confluence on RV implies global confluence. However local confluence on V does not imply local confluence on RV ! For example, let $V = \{v_1, v_2\}$ and let $S_1: v_1 \rightarrow v_1 + 2v_2$, $S_2: v_2 \rightarrow v_2 + 2v_1$. Obviously, S_1, S_2 are locally confluent on V , since for no $v \in V$, $S_1(v)$ and $S_2(v)$ are simultaneously defined. However S_1 and S_2 are not confluent on $\mathbb{R}V$!

Lemma 2.1 $S_1(v_1 + \sqrt{2}v_2)$ and $S_2(v_1 + \sqrt{2}v_2)$ have no common descendant in $\mathbb{R}V$.

Proof Notice that S_i sends $a_1v_1 + a_2v_2$ to $b_1v_1 + b_2v_2$, where

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = M_i \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad \text{and} \quad M_1 = \begin{pmatrix} 1 & 0 \\ 2 & 1 \end{pmatrix}, \quad M_2 = \begin{pmatrix} 1 & 2 \\ 0 & 1 \end{pmatrix}.$$

If $S_1(v_1 + \sqrt{2}v_2)$ and $S_2(v_1 + \sqrt{2}v_2)$ have a common descendant $c_1v_1 + c_2v_2$ for some $c_1, c_2 \in \mathbb{R}$, then for certain products N_1, N_2 of matrices M_1, M_2 ,

$$N_1 M_1 \begin{pmatrix} 1 \\ \sqrt{2} \end{pmatrix} = N_2 M_2 \begin{pmatrix} 1 \\ \sqrt{2} \end{pmatrix} = \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}.$$

Irrationality of $\sqrt{2}$ implies $N_1M_1 = N_2M_2$ as matrices in $SL(2, \mathbb{Z})$. However, M_1, M_2 generate a free semigroup in $SL(2, \mathbb{Z})$. Therefore, $N_1M_1 \neq N_2M_2$ for any N_1, N_2 . \square

Nonetheless, we have

Theorem 2.2 (Linear Diamond Lemma) *Let $\{V_j\}_{j \in J}$ be a family of subsets of V , such that J is a well ordered set and $V_j \subset V_{j'}$ for $j < j'$ and $\bigcup_{j \in J} V_j = V$. Let $\deg(v) = \min \{j : v \in V_j\}$. Consider a family of linear reduction rules on V such that each of them sends an element of V to a linear combination of elements of smaller degree. Then*

- (1) *these reduction rules are terminal,*
- (2) *if this family is locally confluent on V then it is also locally confluent on RV .*

Therefore, by the Diamond Lemma, such a family of reduction rules is globally confluent on RV .

Proof (1) Assume that there is an infinite chain $X_1 \rightarrow X_2 \rightarrow X_3 \rightarrow \dots$. Let $X_i = \sum_j^{n_i} c_{ij} v_{ij}$ and let d_{ik} denote the k th highest degree among degrees of $v_{i,1}, \dots, v_{i,n_i}$. Since $d_{11} \geq d_{21} \geq d_{31} \geq \dots$, the sequence stabilizes at certain place, which we denote by N_1 . In other words $d_{k,1} = d_{N_1,1}$, for all $k \geq N_1$. Let $e_1 = d_{N_1,1}$. Similarly, $d_{N_1,2} \geq d_{N_1+1,2} \geq d_{N_1+2,2} \geq \dots$, stabilizes, let us say, at N_2 th place. Let $e_2 = d_{N_2,2}$. By continuing this process, we construct $e_1 \geq e_2 \geq e_3 \geq \dots$. This sequence stabilizes at some point as well – let us say at s . Then for any $k \geq N_s$, the elements of V appearing in $X_k = \sum_j^{n_i} c_{kj} v_{kj}$ have degrees e_1, \dots, e_s (each of them may be appearing many times). This, however, leads to contradiction since any reduction transformation replaces some v by a linear combination of elements of V of lower degree.

(2) Let $S_1: v_1 \rightarrow \sum_{i=1}^{n_1} b_i w_i$ and $S_2: v_2 \rightarrow \sum_{i=1}^{n_2} c_i z_i$. Assume that $\deg(v_1) < \deg(v_2)$. We need to prove that for any X , $S_1(X), S_2(X)$ have a common descendant. Let $X = a_1 v_1 + a_2 v_2 + X'$, where X' is a linear combination of elements of $V \setminus \{v_1, v_2\}$. Since degrees of w_1, \dots, w_{n_1} are smaller than that of v_2 , the elements w_1, \dots, w_{n_1} are different than v_2 . If, additionally, $z_1, \dots, z_{n_2} \neq v_1$ then

$$(1) \quad S_2 S_1(X) = a_1 \sum_{i=1}^{n_1} b_i w_i + a_2 \sum_{i=1}^{n_2} c_i z_i + X' = S_1 S_2(X)$$

is a common descendant of $S_1(X)$ and $S_2(X)$ and the proof is complete. Therefore, assume now that one of the z_i 's, say z_1 is equal to v_1 . If $a_2 c_1 = 0$ then $S_1 S_2(X) =$

$S_2S_1(X)$ again. However, this may not be the case if $a_2c_1 \neq 0$, since then

$$S_1S_2(X) = (a_1 + a_2c_1) \sum_{i=1}^{n_1} b_i w_i + a_2 \sum_{i=2}^{n_2} c_i z_i + X'$$

and $S_2S_1(X)$ is as in (1). Now, however, $S_1S_2(X) = S_1S_2S_1(X)$ is a common descendant of $S_1(X)$ and $S_2(X)$. \square

$X \in V$ is *irreducible* with respect to a given set of reduction rules if none of these rules applies to X . Denote the set of irreducible elements by V_{irr} . Note that if $\{S_i\}_{i \in I}$ are terminal then $RV/\mathcal{R}(S_i, i \in I)$ is spanned by V_{irr} . The opposite implication does not hold in general.

The combination of confluence and termination is a very strong property of reduction rules.

Theorem 2.3 (1) *For any terminal rules $\{S_i\}_{i \in I}$ for RV the following conditions are equivalent:*

- (a) $S_i, i \in I$, are locally confluent in RV ;
- (b) $S_i, i \in I$, are confluent in RV ;
- (c) For any $x \in RV$ there is a unique element $\psi(x) \in RV_{\text{irr}}$ such that $x \xrightarrow{*} \psi(x)$.

(2) *If any of the above conditions holds then $\psi: RV \rightarrow RV_{\text{irr}}$ is an R -linear map which factors to an isomorphism*

$$\bar{\psi}: RV/\mathcal{R}(S_i, i \in I) \rightarrow RV_{\text{irr}}.$$

Further, ψ is the identity on RV_{irr} , and consequently V_{irr} is a basis of $RV/\mathcal{R}(S_i, i \in I)$.

Proof (a) \Rightarrow (b) This follows by the Diamond Lemma.

(b) \Rightarrow (c) Since the reduction rules are terminal, every $x \in RV$ has a descendant $y \in RV_{\text{irr}}$. By confluence, y is unique – indeed, if $x \xrightarrow{*} y' \neq y$ and $y' \in RV_{\text{irr}}$ then $y \sim y'$ but they have no common descendants, contradicting the confluence assumption.

(c) \Rightarrow (a) This is obvious.

(c) \Rightarrow (2) If $x \xrightarrow{*} y$ then $\psi(x) = \psi(y)$. Since the relation \sim defined at the beginning of Section 2.1 is the smallest equivalence relation on RV generated by $\xrightarrow{*}$, $x \sim y$ implies that $\psi(x) = \psi(y)$. Therefore ψ factors to

$$\bar{\psi}: RV/\mathcal{R}(S_i, i \in I) = RV/\sim \rightarrow RV_{\text{irr}}.$$

If we denote the “obvious” map $RV_{\text{irr}} \rightarrow RV \rightarrow RV/\mathcal{R}(S_i, i \in I)$ by ι then clearly both $\iota\psi$ and $\psi\iota$ are identities on their respective domains. Therefore $\bar{\psi}$ is a bijection and an R -linear map. Finally, ψ is also R -linear, since it is a composition of linear maps

$$RV \rightarrow RV/\mathcal{R}(S_i, i \in I) \xrightarrow{\bar{\psi}} RV_{\text{irr}}. \quad \square$$

Only a few interesting terminal and confluent reduction systems on sets of graphs are known. Most of them appear in the context of representation theory of Lie algebras of rank ≤ 2 and of associated quantum groups, cf Sections 4–7. See Section 8 for other examples.

3 Graphs

3.1 Abstract graphs

In a most general setting, a *labeled graph* is $\Gamma = (\mathcal{V}, \mathcal{E}, t, \tau, \Lambda, \lambda, \nu)$, where \mathcal{V} is a vertex set, \mathcal{E} is the set of *edge directions*, $t: \mathcal{E} \rightarrow \mathcal{V}$ is the *tail map*, $\tau: \mathcal{E} \rightarrow \mathcal{E}$ is the *change of direction involution* which is fixed-point free. Λ is a set of labels and $\lambda: \mathcal{E} \rightarrow \Lambda$ is a labeling function. $\nu: \Lambda \rightarrow \Lambda$ is an involution such that $\nu\lambda = \lambda\tau: \mathcal{E} \rightarrow \Lambda$. The function $t\tau: \mathcal{E} \rightarrow \mathcal{V}$ is called the *head map*.

An edge is a two-element set $\{e, \tau(e)\}$. The *valency* of $v \in \mathcal{V}$ is the number of edge directions e such that $t(e) = v$. As mentioned in Introduction, we will sometimes specify a set of 1-valent vertices $V_{\text{ext}}(\Gamma) \subset V(\Gamma)$, called *external vertices*, and consider it as part of graph structure of Γ . The remaining vertices, $V_{\text{int}}(\Gamma) = V(\Gamma) \setminus V_{\text{ext}}(\Gamma)$, are *internal*.

Most definitions of graphs can be deduced from this one. For example, a *partially directed graph* is $\Gamma = (\mathcal{V}, \mathcal{E}, t, \tau, \emptyset, \Lambda, \lambda, \nu)$, such that $\Lambda = \{\pm 1, 0\}$ and $\nu(x) = -x$. An edge $\{e, \tau(e)\}$ with $\lambda(e) = 0$ is *undirected*. Otherwise, its *direction* is either e or $\tau(e)$ depending on whether $\lambda(e) = 1$ or -1 .

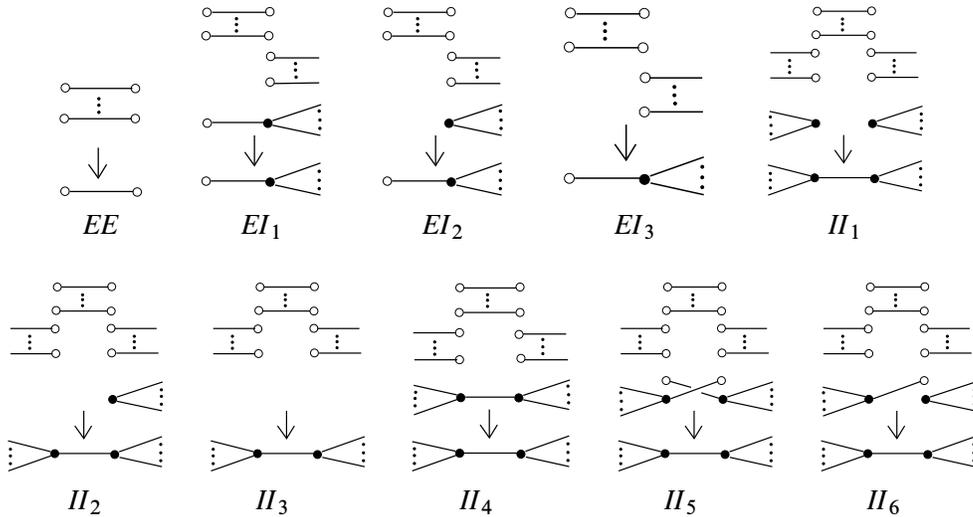
The reason for using edge directions, instead of edges, is that in representation theory one considers graphs whose edges are labeled by representations and have no canonical orientation. If an edge direction is labeled by a representation V then the opposite direction is labeled by the dual of V .

An embedding of Γ_1 into Γ_2 is

- (1) a map $f: V_1 \rightarrow V_2$ which is an embedding of internal vertices of Γ_1 into internal vertices of Γ_2 ,

- (2) a map $g: \mathcal{E}_1 \hookrightarrow \mathcal{E}_2$, such that $t_2g = ft_1$, $\tau_2g = g\tau_1$, and g restricted to $\{e \in \mathcal{E}_1: t(e) \text{ is an internal vertex}\}$ is an embedding.
- (3) an embedding $h: \Lambda_1 \hookrightarrow \Lambda_2$ such that $\lambda_2h = h\lambda_1$ and $v_2h = hv_1$.

For any embedding $f: \Gamma \hookrightarrow \Gamma'$ and $e \in E(\Gamma')$, neighborhood of $f^{-1}(e)$ has one of the following forms:¹



Above, black dots denote internal vertices and white dots the external ones. Triple dots denote several parallel copies (possibly zero). For the purpose of this classification we ignore edge directions.

3.2 Graphs in manifolds

Throughout the paper all manifolds are smooth. A graph in a manifold M , or *manifold graph*, is a subspace $\Gamma \subset M$ which looks locally like 1–dimensional submanifold of M (possibly with boundary) except for *internal vertices*:



For simplicity, we do not allow 2–valent vertices.

The points of $\Gamma \cap \partial M = V_{\text{ext}}(\Gamma)$ are called *external vertices*. Manifold graphs are considered up to isotopy of M fixing ∂M . We denote the set of all vertices of Γ

¹To be precise, one considers the topological realization of Γ and the topological neighborhood of $f^{-1}(e)$.

by $V(\Gamma)$. Note that $\Gamma \setminus V(\Gamma)$ is composed of open intervals and circles (also called loops).

A manifold graph $\Gamma \subset M$ is *labeled* if there is specified a set Λ with an involution $\tau: \Lambda \rightarrow \Lambda$ and a labeling function

$$\lambda: \{\text{orientations of connected components of } \Gamma \setminus V(\Gamma)\} \rightarrow \Lambda.$$

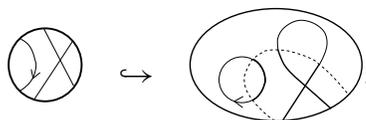
We require that if o, \bar{o} are opposite orientations of the same edge or circle in $\Gamma \setminus V(\Gamma)$ then $\lambda(\bar{o}) = \tau(\lambda(o))$. A graph labeled by $\Lambda = \{0, \pm 1\}$, with $\tau(x) = -x$, is called *partially oriented*. An edge or circle e of Γ is unoriented if $\lambda(e) = 0$ and oriented otherwise. Its orientation is the one labeled by 1.

Note that if M is connected, simply-connected, has connected boundary, and $\dim M \geq 4$ then each graph in M can be thought as a geometric realization of an abstract graph. Such abstract graph is unique up to an insertion or deletion of 2-valent internal vertices into edges or from edges.

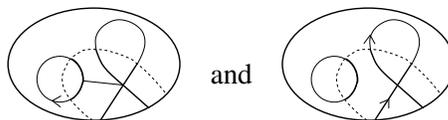
An *embedding* of manifold graph $\Gamma_1 \subset M_1$ into $\Gamma_2 \subset M_2$ is an embedding $f: M_1 \hookrightarrow M_2$ of manifolds of equal dimensions, which embeds a certain representative $\bar{\Gamma}_1$ of the isotopy class of $\Gamma_1 \subset M_1$ into a certain representative $\bar{\Gamma}_2$ of the isotopy class of $\Gamma_2 \subset M_2$ such that f restricted to $\Gamma_1 \setminus V_{\text{ext}}(\Gamma_1)$ is an open map into $\bar{\Gamma}_2$. We identify isotopic embeddings. This definition implies that edges of Γ_1 are mapped either into edges or circles of Γ_2 .

If $\Gamma_1 \subset M_1, \Gamma_2 \subset M_2$ are labeled manifold graphs, then an embedding of Γ_1 into Γ_2 consists of a map $f: M_1 \rightarrow M_2$ as above together with an embedding of the set of labels $\iota: \Lambda_1 \hookrightarrow \Lambda_2$ such that f maps every edge or circle with some orientation, e_1 , of Γ_1 into an edge or circle of Γ_2 , denoted by e_2 with coinciding orientation such that $\lambda_2(e_2) = \iota\lambda_1(e_1)$.

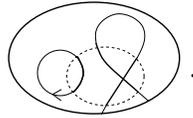
Example 3.1 A graph embedding



and two non-embeddings



The above graph embedding is isotopic and, hence, identified with the embedding



The theory presented in this paper comes in two flavors: oriented and unoriented. In the first case all manifolds are oriented and all embeddings preserve orientations of manifolds. In the latter case, orientations of manifolds do not play any role. In both cases, labelings of edge and circle orientations are preserved. We will stress the difference between oriented and unoriented case whenever necessary, for example in Section 5.

3.3 Linear graphs

Let R be a ring. An R -linear graph is a formal R -linear combination of graphs $\Gamma = \sum_{i=1}^k r_i \Gamma_i$, together with specified bijections $V_{\text{ext}}(\Gamma_1) \simeq V_{\text{ext}}(\Gamma_2) \simeq \dots \simeq V_{\text{ext}}(\Gamma_k)$ such that the corresponding external edge directions have identical labels. (Since each external vertex is 1-valent, its adjacent *external edge direction* is well defined.)

An R -linear manifold graph in M is a formal linear combination $\Gamma = \sum_{i=1}^n r_i \Gamma_i$ of graphs in M such that their external vertices coincide and the outward orientations of the corresponding external edges have identical labels. These graphs are considered up to isotopy of M fixing ∂M . For example,

$$T = \text{[Diagram 1]} - \text{[Diagram 2]}$$

is a non-zero linear graph in D^2 .

3.4 Reduction rules on graphs

We are going to apply the theory of confluence to the problems stated in Introduction, with a particular focus on graphs arising as Kuperberg’s spiders webs. Certain versions of this method were used implicitly already by Jaeger [28], Kuperberg [35; 36] and Yetter [66]. Nonetheless, to our knowledge the subtle difference between local confluence on V and on RV discussed in Section 2.1 has never been observed.

For our purposes, the set of objects, V , considered in Section 2 is either a set of abstract graphs or a set of graphs in a given manifold M .

In the first case, for a given ring R , a *graph reduction rule* is a pair denoted by $T_0 \xrightarrow{S} T$, where T_0 is a graph, $T = \sum_{i=1}^k r_i T_i$ is an R -linear graph and the external vertices

of T_0 and T_i 's are identified via a bijection such that the corresponding external edge directions have identical labels. Any graph reduction rule $T_0 \xrightarrow{S} T$ defines reductions of graphs Γ as follows: For any embedding $\Gamma_0 \hookrightarrow \Gamma$ we obtain new graphs Γ_i by replacing T_0 in Γ by T_i . We say that reduction $\Gamma_0 \rightarrow \sum_{i=1}^k r_i \Gamma_i$ is induced by $T_0 \xrightarrow{S} T$ and we denote that fact by putting S above the arrow, $\Gamma \xrightarrow{S} \sum_{i=1}^k r_i \Gamma_i$. Therefore, unlike in Section 2, we use one symbol (here, S) to denote many reduction rules arising from $T_0 \xrightarrow{S} T$.

Similarly, a *graph reduction rule* for manifold graphs is a pair $T_0 \xrightarrow{S} T$, where T_0 is a graph in some manifold M_0 and $T = \sum_{i=1}^k r_i T_i$ is an R -linear graph in the same manifold such that the external vertices of T_0 and T_i 's coincide and the corresponding external edge orientations have identical labels. For any embedding $M_0 \hookrightarrow M$ and a graph $\Gamma \subset M$ such that $\Gamma \cap M_0 = T_0$, we obtain new graphs $\Gamma_i \subset M$ by replacing T_0 in Γ by T_i . We say that the reduction $\Gamma_0 \rightarrow \sum_{i=1}^k r_i \Gamma_i$ is induced by $T_0 \xrightarrow{S} T$ and we denote that fact by $\Gamma \xrightarrow{S} \sum_{i=1}^k r_i \Gamma_i$.

By analogy to the notation in Section 2, we use $\mathcal{R}(S_i, i \in I) \subset RV$ to denote the submodule generated by all linear graphs $\Gamma - \sum_{i=1}^k r_i \Gamma_i$ coming from graph reductions $\Gamma \xrightarrow{S_i} \sum_{i=1}^k r_i \Gamma_i$, for $i \in I$.

3.5 Proving confluence of reduction rules of abstract graphs

An *overlap* of graphs Γ_1 and Γ_2 is a graph Γ and pair $(\Gamma_1 \hookrightarrow \Gamma, \Gamma_2 \hookrightarrow \Gamma)$ of graph embeddings. If $\{T_{i0} \xrightarrow{S_i} \sum_k r_{ik} T_{ik}\}_{i \in I}$ is a set of reduction rules of abstract graphs with coefficients in R , then each overlap $O = (\iota_1: T_{i0} \hookrightarrow \Gamma, \iota_2: T_{j0} \hookrightarrow \Gamma)$ leads to two different reductions of Γ . We say that reduction rules $\{S_i\}_{i \in I}$ are *locally confluent on* $O = (\Gamma_1 \hookrightarrow \Gamma, \Gamma_2 \hookrightarrow \Gamma)$ if, for any i, j such that $\Gamma_{i0} = \Gamma_1, \Gamma_{j0} = \Gamma_2$, the two reductions $\Gamma \xrightarrow{S_i} \sum_k r_{ik} \Gamma_k$ and $\Gamma \xrightarrow{S_j} \sum_k r_{jk} \Gamma'_k$, arising from this overlap have a common descendant.

Note that $\{S_i\}_{i \in I}$ are locally confluent on V if and only if they are locally confluent on all overlaps of graphs $T_{i0}, i \in I$.

We say that $O = (\iota_1: \Gamma_1 \hookrightarrow \Gamma, \iota_2: \Gamma_2 \hookrightarrow \Gamma)$ factors through $O' = (\iota'_1: \Gamma_1 \hookrightarrow \Gamma', \iota'_2: \Gamma_2 \hookrightarrow \Gamma')$ if there is an embedding $f: \Gamma' \hookrightarrow \Gamma$, such that $\iota_1 = f \iota'_1, \iota_2 = f \iota'_2$. If reduction rules $\{S_i\}_{i \in I}$ are locally confluent on O then they are locally confluent on all overlaps which factor through O . An overlap with no factorizations other than the identity is *irreducible*.

We are going to show that factorizations of the type

$$(\iota'_1: \Gamma_1 \hookrightarrow \Gamma', \iota'_2: \Gamma_2 \hookrightarrow \Gamma') \xrightarrow{f} (\iota_1: \Gamma_1 \hookrightarrow \Gamma, \iota_2: \Gamma_2 \hookrightarrow \Gamma)$$

reduce every overlap to an irreducible one:

- (1) If $V(\Gamma_1) \cup V(\Gamma_2)$ is a proper subset of $V(\Gamma)$ then let Γ' be a graph obtained from Γ by removing vertices in $V(\Gamma) \setminus (V(\Gamma_1) \cup V(\Gamma_2))$. Let $\iota'_1 = \iota_1$, $\iota'_2 = \iota_1$, and let f be the obvious embedding.
- (2) If $V_{\text{int}}(\Gamma_1) \cup V_{\text{int}}(\Gamma_2)$ is a proper subset² of $V_{\text{int}}(\Gamma)$, then let Γ' be a graph obtained from Γ by changing the internal vertices in $V_{\text{int}}(\Gamma) \setminus (V_{\text{int}}(\Gamma_1) \cup V_{\text{int}}(\Gamma_2))$ to external ones. Let f be the obvious embedding.
- (3) If $E(\Gamma_1) \cup E(\Gamma_2) \subset E(\Gamma)$ is a proper subset, then let Γ' be Γ with the edge directions in $E(\Gamma) \setminus (E(\Gamma_1) \cup E(\Gamma_2))$ removed. f is the obvious embedding.
- (4) Let $E_{\text{ext}}(\Gamma)$ denote $\{e \in E(\Gamma) : t(e), h(e) \in V_{\text{ext}}(\Gamma)\}$. If $e_1 \in E_{\text{ext}}(\Gamma_i)$, $\iota_i(e_1) = \iota_j(e_2)$, $e_1 \neq e_2$, for some $i, j \in \{1, 2\}$, then let Γ' be Γ with two extra external vertices v_1, v_2 and two new edge directions $e', \tau(e')$ forming an edge connecting v_1 and v_2 . Let ι'_1, ι'_2 coincide with ι_1, ι_2 , except for ι'_i sending $e_1, \tau(e_1)$ to $e', \tau(e')$ and sending $t(e_1), h(e_1)$ to v_1, v_2 . Let $f(v_1) = t(e)$, $f(v_2) = h(e)$, $f(e') = e$, and let f be the identity on the remaining vertices and edges.
- (5) If $e_1 \in E_{\text{ext}}(\Gamma_i)$ and there is no edge e_2 as in (4) but $\iota_i(t(e_1)) = \iota_j(v)$, $t(e_1) \neq v$, for some $i, j \in \{1, 2\}$, then let Γ' be $\Gamma \setminus \{\iota_i(e_1), \tau(\iota_i(e_1))\}$ with an extra external vertex w and two new edge directions $e', \tau(e')$ forming an edge connecting w and $\iota_i(h(e_1))$. Let ι'_1, ι'_2 coincide with ι_1, ι_2 , except for ι'_i sending $e_1, \tau(e_1)$ to $e', \tau(e')$ and sending $t(e_1)$ to w . Let $f(w) = \iota_i(t(e_1))$, $f(e') = \iota_i(e_1)$, $f(\tau(e')) = \iota_i(\tau(e_1))$, and let f be the identity on the remaining vertices and edge directions.
- (6) If $\iota_1^{-1}(e)$ and $\iota_2^{-1}(e)$ are of type II_5 (as defined at the end of Section 3.1) then consider factorization in Figure 2. (For simplicity the edge directions are ignored.)
Analogously, if $\iota_1^{-1}(e)$ and $\iota_2^{-1}(e)$ are (in some order) of types (II_1, II_5) , (II_1, II_6) , (II_2, II_5) , (II_2, II_6) , (II_3, II_5) , (II_3, II_6) , (II_5, II_6) or (II_6, II_6) then we perform similar factorizations.

Theorem 3.2 *An overlap $O = (\iota_1: \Gamma_1 \hookrightarrow \Gamma, \iota_2: \Gamma_2 \hookrightarrow \Gamma)$ is irreducible iff*

- (1) $V(\Gamma) = V(\Gamma_1) \cup V(\Gamma_2)$.
- (2) $V_{\text{int}}(\Gamma) = V_{\text{int}}(\Gamma_1) \cup V_{\text{int}}(\Gamma_2)$.
- (3) $E(\Gamma) = E(\Gamma_1) \cup E(\Gamma_2)$
- (4) If $e_1 \in E_{\text{ext}}(\Gamma_i)$ and $\iota_i(e_1) = \iota_j(e_2)$ then $j = i$ and $e_1 = e_2$.
- (5) If $e \in E_{\text{ext}}(\Gamma_i)$, $\iota_i(t(e)) = \iota_j(v)$, then $i = j$ and $t(e) = v$.

²Since graph embeddings send internal vertices to internal vertices, $V_{\text{int}}(\Gamma_1) \cup V_{\text{int}}(\Gamma_2) \subset V_{\text{int}}(\Gamma)$.

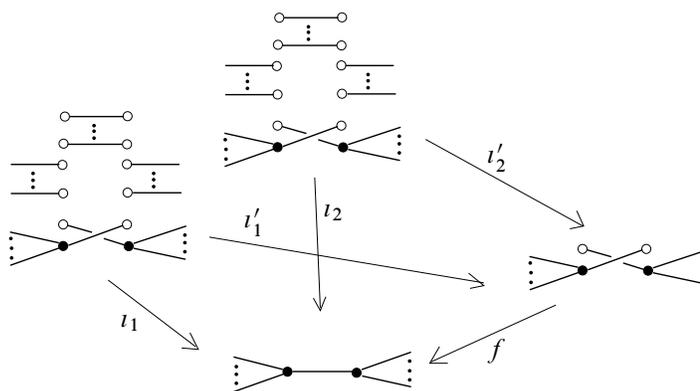


Figure 2

- (6) Γ has no edges of types (II_1, II_5) , (II_1, II_6) , (II_2, II_5) , (II_2, II_6) , (II_3, II_5) , (II_3, II_6) , (II_5, II_5) , (II_5, II_6) , (II_6, II_6) .

Proof \Rightarrow If one of the conditions does not hold then \mathcal{O} admits one of the factorizations described above.

\Leftarrow Suppose that \mathcal{O} satisfies (1)–(6) above and

$$f: (i'_1: \Gamma_1 \hookrightarrow \Gamma', i'_2: \Gamma_2 \hookrightarrow \Gamma') \rightarrow (i_1: \Gamma_1 \hookrightarrow \Gamma, i_2: \Gamma_2 \hookrightarrow \Gamma) = \mathcal{O}$$

is a factorization of \mathcal{O} .

Lemma 3.3 $f: V(\Gamma') \rightarrow V(\Gamma)$ is a bijection.

Proof $f(V(\Gamma')) \supseteq f i'_1 V(\Gamma_1) \cup f i'_2 V(\Gamma_2) = i_1 V(\Gamma_1) \cup i_2 V(\Gamma_2)$ is by (1) equal to $V(\Gamma)$. Therefore, $f: V(\Gamma') \rightarrow V(\Gamma)$ is onto.

Suppose $f(v_1) = f(v_2) = v$ for $v_1 \neq v_2$, $v_1, v_2 \in V(\Gamma')$. By definition of graph embedding, f is 1–1 on $V_{\text{int}}(\Gamma')$. Hence, at least one of the vertices v_1, v_2 is external, say v_1 . Consider two cases:

Case 1 v is external Then v_2 is external as well. Let e_1, e_2 be edge directions with tails v_1, v_2 . Since v is 1–valent, $f(e_1) = f(e_2) := e \in E(\Gamma)$. Since $f(h(e_1)) = f(h(e_2)) = h(e)$, at least one of the vertices $h(e_1), h(e_2)$ is external, contradicting (4).

Case 2 v is internal By (2), we can choose v_2 to be an internal vertex. Since v_1 has valency one, there is a unique vertex w in Γ' connected with v by an edge e' . By (5), w is internal. Let $e = f(e')$. Then the preimage, f^{-1} , of the neighborhood of e must be of type II_5 or II_6 . Since i_1, i_2 satisfy (1)–(4) and factorize through f , they must be of one of the types listed in (6). Contradiction. \square

Corollary 3.4 $f: V_{\text{int}}(\Gamma') \rightarrow V_{\text{int}}(\Gamma)$ and $f: V_{\text{ext}}(\Gamma') \rightarrow V_{\text{ext}}(\Gamma)$ are bijections.

Proof Since f is 1–1 it is enough to prove that (a) $f(V_{\text{int}}(\Gamma')) = V_{\text{int}}(\Gamma)$ and (b) $f(V_{\text{ext}}(\Gamma')) = V_{\text{ext}}(\Gamma)$.

(a) Since f is a graph embedding, $f(V_{\text{int}}(\Gamma')) \subset V_{\text{int}}(\Gamma)$. By (2), $\iota_1(V_{\text{int}}(\Gamma_1)) \cup \iota_2(V_{\text{int}}(\Gamma_2)) = V_{\text{int}}(\Gamma)$, and since ι_1, ι_2 factor through f , $f(V_{\text{int}}(\Gamma')) = V_{\text{int}}(\Gamma)$.

(b) By the previous lemma and by (a), $|V(\Gamma')| = |V(\Gamma)|$, $|V_{\text{int}}(\Gamma')| = |V_{\text{int}}(\Gamma)|$. Hence, $|V_{\text{ext}}(\Gamma')| = |V_{\text{ext}}(\Gamma)|$ and the statement follows from the fact that f is 1–1. \square

Proposition 3.5 $f: E(\Gamma') \rightarrow E(\Gamma)$ is a bijection.

Proof By (3), f is onto. Suppose that $f(e_1) = f(e_2) = e$, $e_1 \neq e_2$. Since f is a bijection on vertices, $t(e_1) = t(e_2)$, $h(e_1) = h(e_2)$. Since $t(e_1)$, $h(e_2)$ are at least 2 valent, they are internal and, consequently, f maps two internal edge directions to a single edge direction and, therefore, it is not a graph embedding. \square

Therefore f is the identity and the proof of Theorem 3.2 is completed. \square

Since each overlap of Γ_1 and Γ_2 satisfying Theorem 3.2(1)–(3) is obtained as a quotient of the disjoint union of Γ_1 and Γ_2 , the number of such overlaps is finite.

Corollary 3.6 Any two abstract graphs have a finite number of irreducible overlaps only.

Consider an overlap of Γ_1 and Γ_2 . By applying factorizations of types (1)–(5), we obtain an overlap satisfying conditions (1)–(5) of Theorem 3.2. Observe, that if an overlap O satisfies these conditions then for every factorization $f: O' \rightarrow O$ of type (6), O' satisfies (1)–(5) as well. Furthermore, observe that for each factorization

$$f: (\iota'_1: \Gamma_1 \hookrightarrow \Gamma', \iota'_2: \Gamma_2 \hookrightarrow \Gamma') \rightarrow (\iota_1: \Gamma_1 \hookrightarrow \Gamma, \iota_2: \Gamma_2 \hookrightarrow \Gamma) = O$$

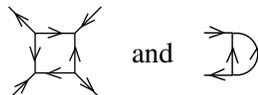
of type (6), either (a) the number of connected components of Γ' is larger than the number of components of Γ , or (b) the number of cycles of Γ' is lower than the number of cycles of Γ . Since the number of connected components is bounded above by the (unchanging) number of vertices, every sequence of factorizations of type (6) is finite. Therefore, we proved:

Corollary 3.7 (1) Each overlap can be reduced to an irreducible one by a finite number of factorizations of types (1)–(6).

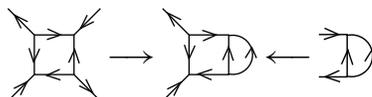
(2) $\{T_{i0} \xrightarrow{S_i} T_i\}_{i \in I}$ are locally confluent if they are locally confluent on all irreducible overlaps of pairs of graphs in $\{T_{i0}\}_{i \in I}$.

Therefore, one has an effective procedure for deciding whether any finite set of reduction rules on graphs is locally confluent.

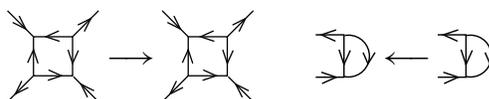
Example 3.8 The graphs



have 5 different irreducible overlaps: four overlaps of the form



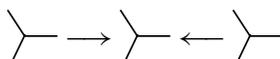
and one “trivial” overlap



Example 3.9 The graphs

$$\Gamma_1 = \Gamma_2 = \text{Y-shape}$$

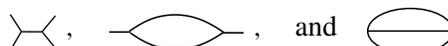
have three different irreducible overlaps of the form



and one trivial overlap,



Notice that the embeddings of Γ_1, Γ_2 into



are not irreducible since they factor through the trivial overlap.

3.6 Proving confluence of reduction rules of surface graphs

An *overlap* of manifold graphs $\Gamma_1 \subset M_1, \Gamma_2 \subset M_2$ is a graph Γ in a manifold M together with isotopy classes of embeddings $(\Gamma_1, M_1) \hookrightarrow (\Gamma, M), (\Gamma_2, M_2) \hookrightarrow (\Gamma, M)$.

$$f: \mathcal{O}' = ((\Gamma_1, M_1) \hookrightarrow (\Gamma', M'), (\Gamma_2, M_2) \hookrightarrow (\Gamma', M')) \rightarrow ((\Gamma_1, M_1) \hookrightarrow (\Gamma, M), (\Gamma_2, M_2) \hookrightarrow (\Gamma, M)) = \mathcal{O}$$

is a factorization of O , if for certain representatives

$$\iota'_1: (\Gamma_1, M_1) \hookrightarrow (\Gamma, M) \quad \text{and} \quad \iota'_2: (\Gamma_2, M_2) \hookrightarrow (\Gamma, M),$$

of embeddings of O' , $f\iota_1$ and $f\iota_2$ belong to isotopy classes of embeddings of O .

As before, given reduction rules, $\{T_{i0} \xrightarrow{S_i} \sum_k r_{ik} T_{ik}\}_{i \in I}$, where S_i takes place in a manifold M_i , each overlap $O = (\iota_1: (T_{i0}, M_i) \hookrightarrow (\Gamma, M), \iota_2: (T_{j0}, M_j) \hookrightarrow (\Gamma, M))$ leads to two different reductions of Γ . Rules $\{S_i\}_{i \in I}$ are locally confluent if they are locally confluent on all overlaps of graphs T_{i0} , $i \in I$. As before we consider factorization of overlaps and observe that if rules $\{S_i\}_{i \in I}$ are locally confluent on O then they are locally confluent on all overlaps which factor through O .

A factorization $f: O' \rightarrow O$ is trivial if $f: M' \rightarrow M$ is isotopic to a homeomorphism. As before, an overlap is *irreducible* if it does not admit a non-trivial factorization.

In this section we are going to develop an algorithm for proving local confluence of overlaps of surface graphs. Observe that we cannot apply verbatim the method of the previous section to our current setting since Corollary 3.6 and Corollary 3.7(1) and (2) fail for surface graphs:

Lemma 3.10 (1) *If every component of F has a non-empty boundary then no overlap $((\Gamma_1, F_1) \hookrightarrow (\Gamma, F), (\Gamma_2, F_2) \hookrightarrow (\Gamma, F))$ is irreducible.*

(2) *If every component of F has a non-empty boundary then no overlap $((\Gamma_1, F_1) \hookrightarrow (\Gamma, F), (\Gamma_2, F_2) \hookrightarrow (\Gamma, F))$ factors through an irreducible one.*

(3) *If F is closed, $F \neq S^2, RP^2$, and Γ is either empty or it is a contractible loop in F , then (Γ, F) has infinitely many irreducible overlaps with itself.*

Proof (1) Let F' be F with a disk removed from one of its components, C . By imagining the disk lying “very close” to ∂C , one can isotope ι_1, ι_2 to ι'_1, ι'_2 so that $\iota'_1(F_1) \cup \iota'_2(F_2) \subset F'$. Consequently, (ι_1, ι_2) factors through $(\iota'_1: (\Gamma_1, F_1) \hookrightarrow (\Gamma', F'), \iota'_2: (\Gamma_2, F_2) \hookrightarrow (\Gamma', F'))$ via the embedding $f: F' \rightarrow F$. This is a non-trivial factorization, contradicting the initial assumption.

(2) If an overlap as above factors through $(\iota_1: (\Gamma_1, F_1) \hookrightarrow (\tilde{\Gamma}, \tilde{F}), \iota_2: (\Gamma_2, F_2) \hookrightarrow (\tilde{\Gamma}, \tilde{F}))$ then $\tilde{F} \subset F$ and consequently, every component of \tilde{F} has a non-empty boundary.

(3) For any diffeomorphism $f: (\Gamma, F) \rightarrow (\Gamma, F)$, diffeomorphisms $\iota_1 = f: (\Gamma, F) \rightarrow (\Gamma, F)$ and the identity map $\iota_2 = f: (\Gamma, F) \rightarrow (\Gamma, F)$ form an irreducible overlap which we denote by O_f . Notice that $O_f = O_{f'}$ if and only if f' is isotopic to f . Since the mapping class group of F is infinite, there are infinitely many irreducible overlaps of this type. \square

We will attempt to resolve these difficulties now. $\{O_j\}_{j \in J}$ is a *basis* of overlaps of (Γ_1, F_1) and (Γ_2, F_2) if every overlap of these surface graphs factors through O_j for some $j \in J$.

Corollary 3.11 *The rules $S_i: \Gamma_{i0} \rightarrow \sum_k r_{ik} \Gamma_{ik}$, $i \in I$, are locally confluent, if they are locally confluent on a certain basis of overlaps of pairs of graphs in $\{(\Gamma_{i0}, F_i)\}_{i \in I}$.*

Lemma 3.10(2) shows that not every pair of graphs in surfaces has a finite basis of overlaps. Furthermore, basis of overlaps are generally not unique. Nonetheless, we are going to show that any two simple graphs in surfaces have a finite basis of overlaps. We say that $\Gamma \subset F$ is *simple* if Γ is connected and every component C of $F \setminus \Gamma$ is either D^2 or an annulus whose one boundary component lies in Γ and the other in ∂F .

Theorem 3.12 *Any two simple graphs have a finite basis of overlaps.*

Our proof is also an algorithm for finding such a finite basis.

For any graph $\Gamma \hookrightarrow F$ there is an $\varepsilon_0 > 0$ such that ε -neighborhoods of Γ in F are diffeomorphic to each other for all $\varepsilon < \varepsilon_0$. Denote such ε -neighborhood by $\nu(\Gamma)$ and we call it a framing of Γ . Each framing of Γ retracts onto Γ and each finite abstract graph has finitely many different framings only.

Any overlap of $(\Gamma_1, \nu(\Gamma_1))$ and $(\Gamma_2, \nu(\Gamma_2))$ factors through an overlap

$$\iota_1: (\Gamma_1, \nu(\Gamma_1)) \hookrightarrow (\Gamma, F), \iota_2: (\Gamma_2, \nu(\Gamma_2)) \hookrightarrow (\Gamma, F),$$

such that $(\iota_1: \Gamma_1 \hookrightarrow \Gamma, \iota_2: \Gamma_2 \hookrightarrow \Gamma)$ is an irreducible overlap of abstract graphs and F is a framing of Γ . Consequently, such overlaps form a basis of overlaps of $(\Gamma_1, \nu(\Gamma_1))$ and $(\Gamma_2, \nu(\Gamma_2))$. Denote them by O_1, \dots, O_d .

Now assume that Γ_1 and Γ_2 are embedded into F_1, F_2 in such way that they are simple graphs. We extend each basic overlap

$$O_i = (\iota_1: (\Gamma_1, \nu(\Gamma_1)) \hookrightarrow (\Gamma, F), \iota_2: (\Gamma_2, \nu(\Gamma_2)) \hookrightarrow (\Gamma, F))$$

constructed above to an overlap of (Γ_1, F_1) and (Γ_2, F_2) as follows: Every component B of ∂F , disjoint from Γ , is parallel to a unique cycle $\alpha_B \subset \Gamma$. If the preimage $\iota_i^{-1}(\alpha_B)$ for either $i = 1$ or 2 is a circle in F_i which bounds a disk $D_i \subset F_i$ containing $\iota_i^{-1}(B)$ then we attach a disk to F along B and we extend ι_i over D_i for those $i = 1, 2$ which satisfy the above condition. By performing these operations for all components of ∂F disjoint from Γ , we extend O_i to an overlap \bar{O}_i of (Γ_1, F_1) and (Γ_2, F_2) . Notice that every overlap of these graphs which restricts to O_i must factor through \bar{O}_i . Therefore we proved

Corollary 3.13 $\bar{O}_1, \dots, \bar{O}_d$ is a basis of overlaps of (Γ_1, F_1) and (Γ_2, F_2) .

4 A_1 -webs

Interesting examples of confluent and terminal reduction rules come from Kuperberg’s spider webs associated with simple Lie algebras of rank ≤ 2 . These are spaces of graphs in D^2 considered modulo certain relations, of the type defined in Introduction. The classes of graphs considered and the relations between them depend on the Lie algebra in question. Because of their relations to quantum invariants, it is important to consider Kuperberg’s webs in surfaces other than D^2 , even though they are not spiders anymore, since the join operation is no longer defined. For that reason Kuperberg’s graphs in surfaces other than D^2 will simply be called *webs*. Although Kuperberg’s original reduction rules are not confluent for webs we will show that these rules can be extended to finite, confluent, and terminal sets of reduction rules.

The A_1 -webs without external vertices are unoriented link diagrams. To put such diagrams in the framework of surface graphs, we define *crossings* as marked 4-valent vertices depicted as



We require that opposite edges meeting at any crossing have equal labels, when taken with coinciding orientations. The notions of linear graphs, reduction rules, local and global confluence extend to graphs with crossings in an obvious way. Furthermore, the method of proving local confluence discussed in Section 3.6 holds for graphs with crossings as well.

Consider now a surface F (not necessarily oriented) with a distinguished set of base points $B \subset \partial F$ (possibly empty). An A_1 -web in (F, B) is an unoriented graph all of whose internal vertices are crossings and all of whose external vertices are points of B . (Such graphs in D^2 are called *unoriented tangle diagrams* with endpoints in B .) We denote the set of all A_1 -webs in (F, B) by $\mathcal{W}_{A_1}(F, B)$. Let R be a fixed ring with a distinguished invertible element A . The A_1 -web space over R is the R -module

$$\mathbb{A}_1(F, B, R) = R\mathcal{W}_{A_1}(F, B)/\mathcal{R}(T_1, T_2),$$

where

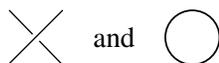
$$T_1 = \left(\begin{array}{c} \diagup \diagdown \\ \diagdown \diagup \end{array} - A \right) \left(-A^{-1} \begin{array}{c} \frown \\ \smile \end{array} \right)$$

$$T_2 = \bigcirc + (A^2 + A^{-2})\emptyset.$$

Here and further on, all relations take place in D^2 and all 1-valent vertices are external, unless stated otherwise. The above relations suggest the obvious reduction rules:

$$S_1: \begin{array}{c} \diagup \\ \diagdown \end{array} \rightarrow A \left(+ A^{-1} \begin{array}{c} \frown \\ \smile \end{array} \right), \quad S_2: \bigcirc \rightarrow -(A^2 + A^{-2})\emptyset.$$

Denote the number of crossings and connected components of $\Gamma \in \mathcal{W}_{A_1}(F, B)$ by $v(\Gamma)$ and $c(\Gamma)$, respectively. If $\mathbb{Z}_{\geq 0} \times \mathbb{Z}_{\geq 0}$ is given the lexicographic ordering then these reduction rules replace each graph Γ by a combination of graphs Γ_i such that $(v(\Gamma_i), c(\Gamma_i)) < (v(\Gamma), c(\Gamma))$. Therefore, the rules S_1, S_2 are terminal. The irreducible graphs are those with no crossings and no contractible loops. Since



have no non-trivial overlaps, they are locally confluent and, hence, also globally confluent. Now Theorem 2.3(2) provides answers to questions (1) and (2) of Section 1:

Corollary 4.1 *For any F, R and q , $\mathbb{A}_1(F, B, R)$ is the free R -module with a basis given by finite collections of disjoint non-trivial simple closed loops in F , including \emptyset .*

5 A_2 -webs

Let F be a surface with a distinguished set of base points $B \subset \partial F$ (possibly empty) which are marked by ± 1 . An A_2 -web in (F, B) is an oriented graph Γ in F all of whose internal vertices are either 3-valent sinks or sources or 4-valent crossings:



and such that all external vertices are points of B . Furthermore, we require that the external edge adjacent to $b \in B$ is oriented inwards or outwards according to the labeling of b by 1 or -1 .

Denote the set of A_2 -webs in F by $\mathcal{W}_{A_2}(F, B)$. The A_2 -web space is

$$\mathbb{A}_2(F, B, R) = R\mathcal{W}_{A_2}(F, B)/\mathcal{R}(T_1, T_2, T_3, T_4, T_5, T_6),$$

where

$$\begin{aligned}
 T_1 &= \text{circle with arrow} - (q + 1 + q^{-1})\emptyset, & T_2 &= \text{circle with arrow} - (q + 1 + q^{-1})\emptyset, \\
 T_3 &= \text{circle with two arrows} + (q^{\frac{1}{2}} + q^{-\frac{1}{2}})\text{circle with arrow}, & T_4 &= \text{square with arrows} - \text{crossing} - \text{crossing}, \\
 T_5 &= \text{crossing} - q^{\frac{1}{6}} \text{trivalent vertex} - q^{-\frac{1}{3}} \text{trivalent vertex}, & T_6 &= \text{crossing} - q^{-\frac{1}{6}} \text{trivalent vertex} - q^{\frac{1}{3}} \text{trivalent vertex}.
 \end{aligned}$$

and R is an arbitrary ring with a distinguished invertible element denoted by $q^{\pm\frac{1}{6}} \in R$. ($R = \mathbb{C}[q^{\pm\frac{1}{6}}]$ in Kuperberg [36].)

The above relations suggest “obvious” reduction rules

$$\begin{aligned}
 S_1: \text{circle with arrow} &\rightarrow (q + 1 + q^{-1})\emptyset, & S_2: \text{circle with arrow} &\rightarrow (q + 1 + q^{-1})\emptyset, \\
 S_3: \text{circle with two arrows} &\rightarrow -(q^{\frac{1}{2}} + q^{-\frac{1}{2}})\text{circle with arrow}, & S_4: \text{square with arrows} &\rightarrow \text{crossing} + \text{crossing}, \\
 S_5: \text{crossing} &\rightarrow q^{\frac{1}{6}} \text{trivalent vertex} + q^{-\frac{1}{3}} \text{trivalent vertex}, & S_6: \text{crossing} &\rightarrow q^{-\frac{1}{6}} \text{trivalent vertex} + q^{\frac{1}{3}} \text{trivalent vertex}.
 \end{aligned}$$

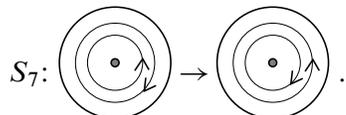
Denote the number of connected components, 3-valent vertices, and crossings of any $\Gamma \in \mathcal{W}_{A_2}(F, B)$ by $c(\Gamma)$, $v_3(\Gamma)$, and $v_4(\Gamma)$, respectively. If $\mathbb{Z}_{\geq 0} \times \mathbb{Z}_{\geq 0} \times \mathbb{Z}_{\geq 0}$ is given the lexicographic ordering, then the above reduction rules replace Γ by a linear combination of graphs Γ_i such that $(v_4(\Gamma_i), v_3(\Gamma_i), c(\Gamma_i)) < (v_4(\Gamma), v_3(\Gamma), c(\Gamma))$. Consequently, these reduction rules are terminal. However, they are not confluent for $F \neq D^2, S^2$! Indeed, any surface $F \neq D^2, S^2$ contains an annulus whose core is not contractible in F and the two possible applications of S_4 to

$$\Gamma = \text{annulus with arrows},$$

followed by S_1, S_2 , reduce it to $X_1 + (q + 1 + q^{-1})\emptyset$ and $X_2 + (q + 1 + q^{-1})\emptyset$, where

$$X_1 = \text{annulus with arrows} \quad \text{and} \quad X_2 = \text{annulus with arrows}.$$

Since X_1 and X_2 are irreducible and not isotopic, the reduction rules are not confluent. In order to remedy this imperfection, we need to consider an additional reduction rule taking place in an annulus:



Note that S_1, \dots, S_7 are terminal in the oriented case but not terminal in the unoriented case, c.f. last paragraph of Section 3.2. Indeed, S_7 is its own inverse in the unoriented case! Therefore, we consider A_2 -webs in oriented surfaces only and work in the category of oriented surfaces from now on. (We assume that all surfaces appearing in reduction rules S_1, \dots, S_7 have counterclockwise orientation.)

One checks all overlaps for S_1, \dots, S_7 and concludes that S_1, \dots, S_7 are locally confluent on all of them³. Therefore, by Theorem 2.3, we conclude:

Corollary 5.1 *The reduction rules S_1, \dots, S_7 are both terminal and confluent for graphs in $\mathcal{W}_{A_2}(F, B)$, for any oriented surface F and any set of marked base points $B \subset \partial F$. Consequently, $\mathbb{A}_2(F, B, R)$ is a free R -module with a basis composed of irreducible graphs in $\mathcal{W}_{A_2}(F, B)$.*

Observe that irreducible A_2 -webs in D^2 are those which have no S^1 's, no internal bi-gons, and no internal 4-gons. (Such graphs in D^2 are called *non-elliptic* by Kuperberg [36].) While these terms are intuitively obvious for graphs in D^2 , they do require clarification for graphs in other surfaces.

Components of $F \setminus \Gamma$ are *faces of Γ* . A face is *internal* if it is disjoint from ∂F . An internal face is called an *n-gon* if it is a disk bounded by a sequence of n edges of Γ . (The orientations of the edges are irrelevant.) An *n-gon* is *true* if all its boundary edges are distinct; otherwise it is *fake*. For example, the 4-gon in $S^1 \times I$ bounded by the edges E_1, E_2, E_3, E_2 depicted in Figure 3 is fake.

A loop in Γ bounding a disk in $F \setminus \Gamma$ is called a 0-gon. The next statement follows directly from A_2 -web reduction rules:

Corollary 5.2 *The irreducible graphs in $\mathcal{W}_{A_2}(F, B)$ are precisely those with no 0-gons, no true bi-gons, and no true 4-gons.*

³ Recall that irreducible overlaps of S_3 and S_4 (as abstract graphs) were classified in Example 3.8.

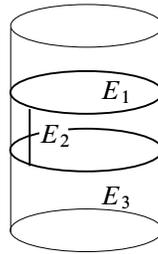


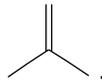
Figure 3

6 B_2 -webs

Let F be a surface together with a specified finite set of base points $B \subset \partial F$ (possibly empty), each of them marked by 1 or 2. Throughout this section we work in the category of unoriented surfaces.

Definition 6.1 Let $\mathcal{W}_{B_2}(F, B)$ be the set of all labeled graphs Γ in F , with $\Lambda = \{1, 2\}$ and ν the identity, c.f. Section 3, such that

- (1) the labels of edges adjacent to points of B coincide with their labels, and
- (2) all internal vertices of Γ are of the form



(The labels are depicted either by a single or double line.)

The B_2 -web space is

$$\mathbb{B}_2(F, B, R) = R\mathcal{W}_{B_2}(F, B)/\mathcal{R}(T_1, \dots, T_6),$$

where

$$\begin{aligned}
 T_1 &= \bigcirc + (q^2 + q + q^{-1} + q^{-2})\emptyset & T_2 &= \bigcirc\bigcirc - (q^3 + q + 1 + q^{-1} + q^{-3})\emptyset \\
 T_3 &= \text{double line} \bigcirc & T_4 &= \text{double line} \bigcirc \text{double line} + (q + 2 + q^{-1}) \text{double line} \\
 T_5 &= \text{triangle with double lines} & T_6 &= \text{crossing} - \text{crossing} + \text{cup} - \text{cup}
 \end{aligned}$$

and R is an arbitrary ring with a distinguished invertible element $q \in R$. B_2 -webs with crossings are discussed in the next subsection.

While T_1, \dots, T_5 yield “obvious” reduction relations, which we denote by S_1, \dots, S_5 , relation T_6 creates a problem since the rule

$$\begin{array}{c} \diagup \quad \diagdown \\ \diagdown \quad \diagup \end{array} \rightarrow \begin{array}{c} \diagup \quad \diagdown \\ \diagup \quad \diagdown \end{array} - \begin{array}{c} \diagdown \quad \diagup \\ \diagdown \quad \diagup \end{array} + \begin{array}{c} \diagdown \quad \diagup \\ \diagdown \quad \diagup \end{array}$$

is its own inverse and, hence, it is not terminal. Following Kuperberg’s idea, we remedy this problem by allowing B_2 -webs to have 4-valent vertices subject to a relation $T'_6 = 0$, where

$$T'_6 = \begin{array}{c} \diagup \quad \diagdown \\ \diagdown \quad \diagup \end{array} - \begin{array}{c} \diagdown \quad \diagup \\ \diagdown \quad \diagup \end{array} - \begin{array}{c} \diagdown \quad \diagup \\ \diagdown \quad \diagup \end{array}.$$

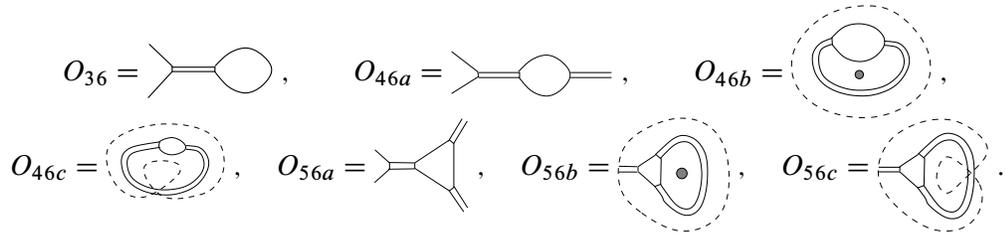
We denote this extended family of webs by $\mathcal{W}'_{B_2}(F, B)$. Note that T'_6 does not introduce any new relations and, therefore,

$$\mathbb{B}_2(F, B, R) = R\mathcal{W}_{B_2}(F, B)/\mathcal{R}(T_1, \dots, T_6) = R\mathcal{W}'_{B_2}(F, B)/\mathcal{R}(T_1, \dots, T_5, T'_6).$$

Now, T'_6 suggests the reduction rule

$$S_6: \begin{array}{c} \diagup \quad \diagdown \\ \diagdown \quad \diagup \end{array} \rightarrow \begin{array}{c} \diagdown \quad \diagup \\ \diagdown \quad \diagup \end{array} + \begin{array}{c} \diagdown \quad \diagup \\ \diagdown \quad \diagup \end{array}$$

Since each of the reduction rules S_1, \dots, S_6 either decreases the number of vertices or decreases the number of connected components without increasing the number of vertices, these reduction rules are terminal. However, they are not confluent in general⁴. S_1, \dots, S_6 have the following basis of overlaps:



Dashed lines denote boundaries of surfaces. (No dashed line is drawn for diagrams in D^2 .) Overlaps O_{46b} and O_{56b} take place in annuli and O_{46c} and O_{56c} in Möbius bands. Unfortunately, S_1, \dots, S_6 are not locally confluent on these overlaps. For example,

$$0 \xleftarrow{S_3} \begin{array}{c} \diagup \quad \diagdown \\ \diagdown \quad \diagup \end{array} \xrightarrow{S_6, S_1} \begin{array}{c} \diagdown \quad \diagup \\ \diagdown \quad \diagup \end{array} - (q^2 + q + q^{-1} + q^{-2}),$$

and both of these linear graphs are irreducible with respect to S_1, \dots, S_6 . In order to remedy that, we introduce the following new rules (preserving relations $S_1 - S_6$):

⁴ These rules may be confluent for certain choices of R and q , but not for all.

$$\begin{aligned}
 S_7: & \text{ } \bigcirc \rightarrow (q^2 + q + q^{-1} + q^{-2}) \bigcirc, & S_8: & \text{ } \bigcirc = \rightarrow -(q + 2 + q^{-1}) \bigcirc =, \\
 S_9: & \text{ } \bigtriangle \rightarrow (q + 2 + q^{-1}) \bigtriangle, \\
 S_{10}: & \text{ } \bigcirc \rightarrow -(q + 2 + q^{-1}) \bigcirc + (q^2 + q + q^{-1} + q^{-2}) \bullet, \\
 S_{11}: & \text{ } \bigcirc \rightarrow -(q + 2 + q^{-1}) \bigcirc + (q^2 + q + q^{-1} + q^{-2}) \bigcirc, \\
 S_{12}: & \text{ } \bigcirc \rightarrow 0, & S_{13}: & \text{ } \bigcirc \rightarrow 0.
 \end{aligned}$$

Rules S_{10}, S_{12} take place in annuli and rules S_{11}, S_{13} in Möbius bands. (The graph on the left side of rule S_{11} has a single vertex, and the one on the left side of S_{13} has two vertices.)

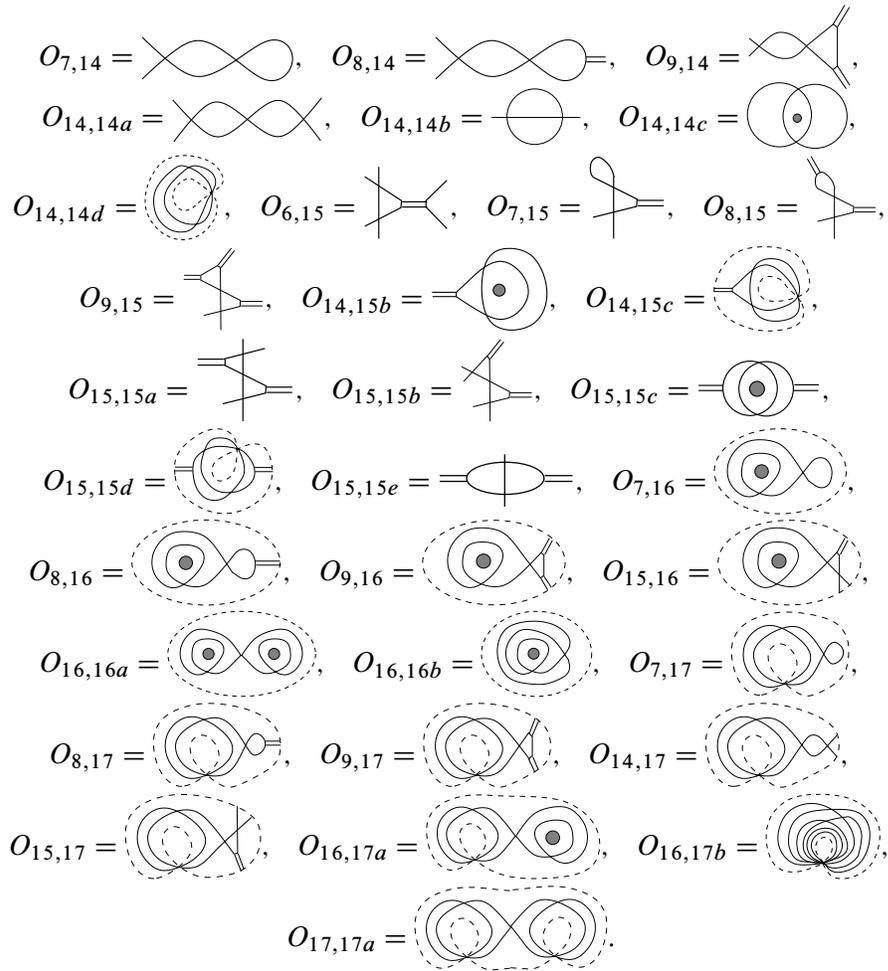
Now S_1, \dots, S_{13} are locally confluent on O_{36}, \dots, O_{56c} , but the new rules, $S_7 - S_{13}$, lead to new overlaps:

$$\begin{aligned}
 O_{77} &= \infty, & O_{68} &= \bigcirc \bigcirc, & O_{78} &= \infty =, & O_{88} &= = \infty =, \\
 O_{69a} &= \bigtriangle, & O_{69b} &= \bigtriangle \bullet, & O_{69c} &= \bigtriangle \bigcirc, & O_{79} &= \bigtriangle \bigcirc, \\
 O_{89} &= = \bigtriangle \bigcirc, & O_{99} &= \bigtriangle \bigtriangle, & O_{6,12} &= \bigcirc \bigcirc \bullet, & O_{6,13} &= \bigcirc \bigcirc \bigcirc.
 \end{aligned}$$

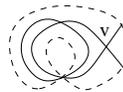
Now, we make S_1, \dots, S_{13} locally confluent on these overlaps by introducing the following new reduction rules:

$$\begin{aligned}
 S_{14}: & \text{ } \bigcirc \rightarrow -(q + 2 + q^{-1}) \bigcirc - (q^2 + 2q + 2 + 2q^{-1} + q^{-2}) \bigcirc, \\
 S_{15}: & \text{ } \bigtriangle \rightarrow (q + 2 + q^{-1}) \left(\bigtriangle + \bigtriangle \right), \\
 S_{16}: & \text{ } \bigcirc \rightarrow (q + 2 + q^{-1}) \bigcirc - (q^2 + q + q^{-1} + q^{-2}) \bullet, \\
 S_{17}: & \text{ } \bigcirc \rightarrow (q + 2 + q^{-1}) \bigcirc - (q^2 + q + q^{-1} + q^{-2}) \bigcirc.
 \end{aligned}$$

The new overlaps now are:



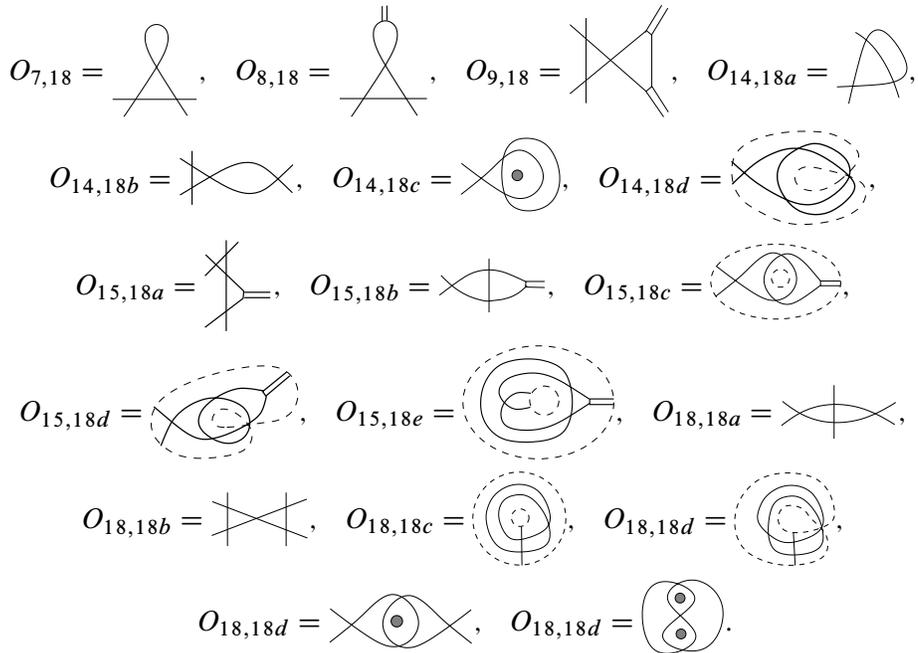
Finally, there is an overlap $O_{17,17b}$ in a Klein bottle obtained by gluing two Möbius bands along their boundaries and taking a union Γ of two graphs



overlapping at vertex v . (Hence, Γ has three 4-valent vertices and no vertices of other valences.) Since S_1-S_{17} are not locally confluent on $O_{6,15}$, we add yet another reduction rule:

$$S_{18}: \text{Diagram} \rightarrow (q+2+q^{-1}) \left(\text{Diagram 1} + \text{Diagram 2} + \text{Diagram 3} \right) + (q^2+4q+6+4q^{-1}+q^{-2}) \text{Diagram 4}.$$

One can check that S_1-S_{18} are locally confluent on all overlaps listed so far. However, S_{18} leads to new overlaps:



By checking all of the above overlaps, we conclude that S_1-S_{18} are locally confluent on all of them! Therefore, we proved:

Theorem 6.2 *The reduction rules S_1, \dots, S_{18} are both terminal and confluent for $\mathcal{W}_{B_2}(F, B)$, for any surface F and $B \subset \partial F$ (both in orientable and unorientable categories).*

For sets $B \subset \partial F$ all of whose points are marked by 1, denote the set of all graphs in $\mathcal{W}_{B_2}(F, B)$ with single edges only (that is, edges labeled by 1), by $\mathcal{W}'_{B_2}(F, B)$. (Graphs in $\mathcal{W}'_{B_2}(F, B)$ may include double loops.)

Proposition 6.3 *For any F and $B \subset \partial F$ as above,*

(1) *the embedding $\mathcal{W}'_{B_2}(F, B) \hookrightarrow \mathcal{W}_{B_2}(F, B)$ induces an isomorphism*

$$\phi: RW'_{B_2}(F, B)/\mathcal{R}(S_1, S_2, S_7, S_{10}, S_{11}, S_{14}, S_{16}, S_{17}) \rightarrow \mathbb{B}_2(F, B, R).$$

(2) *the rules $S_1, S_2, S_7, S_{10}, S_{11}, S_{14}, S_{16}, S_{17}$ are terminal and confluent for graphs in $\mathcal{W}'_{B_2}(F, B)$.*

Proof Since internal double edges are resolvable by S_6 , ϕ is onto. The map ϕ is 1–1 as well: If $\phi(x) = 0$ in $\mathcal{W}_{B_2}(F, B)$, then by confluence of S_1 – S_{18} , x can be reduced to 0 by these rules. Since $x \in R\mathcal{W}'_{B_2}(F, B)$, the rules which do not contain double edges are sufficient to reduce x to 0. \square

6.1 B_2 –webs with crossings

For any F and $B \subset \partial F$ as in Section 6, let $\mathcal{W}_{B_2}^c(F, B)$ be the set of all labeled graphs Γ in F , with edges labeled by 1 and 2 such that

- (1) the labels of edges adjacent to points of B coincide with their labels,
- (2) all internal vertices of Γ are of the form



Resolutions of crossings are provided by

$$\begin{aligned}
 C_1: & \text{X} \rightarrow -q^{\frac{1}{2}} \left(-q^{-\frac{1}{2}} \text{C} + \frac{1}{q^{\frac{1}{2}} + q^{-\frac{1}{2}}} \text{X} \right) \\
 C_2: & \text{X} \rightarrow \frac{q^{-\frac{1}{2}}}{q^{\frac{1}{2}} + q^{-\frac{1}{2}}} \text{Y} + \frac{q^{\frac{1}{2}}}{q^{\frac{1}{2}} + q^{-\frac{1}{2}}} \text{Z} \\
 C_3: & \text{X} \rightarrow \frac{q^{\frac{1}{2}}}{q^{\frac{1}{2}} + q^{-\frac{1}{2}}} \text{Y} + \frac{q^{-\frac{1}{2}}}{q^{\frac{1}{2}} + q^{-\frac{1}{2}}} \text{Z} \\
 C_4: & \text{X} \rightarrow q \left(+q^{-1} \text{C} + \frac{1}{q + 2 + q^{-1}} \text{D} \right)
 \end{aligned}$$

Since the crossing diagrams do not add any new overlaps, we conclude with:

Corollary 6.4 *If $q^{\frac{1}{2}} \in R$ is such that $q + 1$ is invertible in R , then resolutions S_1, \dots, S_{18} together with C_1, \dots, C_4 are confluent and terminal for any surface F and $B \subset \partial F$.*

7 G_2 –webs

Let F be a surface together with a specified finite set of base points $B \subset \partial F$ (possibly empty), each of them marked by 1 or 2. Throughout this section we work in the category of unoriented surfaces.

(taking place in annulus) are confluent and terminal.⁵

8 Partition category and dichromatic reduction rules

An example of terminal and confluent reduction rules for abstract graphs comes from the dichromatic polynomial, cf Yetter [66].

Let \mathcal{G}_n be the set of all unoriented graphs with n external vertices labeled from 1 to n and let $R = \mathbb{Z}[p, q, s, v, w_1, w_2]$. Consider reduction rules

$$\begin{aligned}
 S_{k,l}: k \left\{ \begin{array}{c} \text{---} \circ \text{---} \\ \vdots \\ \text{---} \circ \text{---} \end{array} \right\} l &\rightarrow p \begin{array}{c} \text{---} \circ \\ \vdots \\ \text{---} \circ \end{array} + q \begin{array}{c} \text{---} \circ \text{---} \\ \vdots \\ \text{---} \circ \text{---} \end{array}, \\
 S_l: \left\{ \begin{array}{c} \text{---} \circ \text{---} \\ \vdots \\ \text{---} \circ \text{---} \end{array} \right\} l &\rightarrow s \begin{array}{c} \text{---} \circ \\ \vdots \\ \text{---} \circ \end{array}, \\
 S_v: \circ &\rightarrow v \emptyset, \\
 S_{bw}: \bullet \text{---} \circ &\rightarrow w_1 \bullet \\
 S_{bwb}: \bullet \text{---} \circ \text{---} \bullet &\rightarrow w_2 \bullet \text{---} \bullet
 \end{aligned}$$

where external (respectively, internal) vertices are denoted by black (respectively, white) nodes and $k, l \in \mathbb{Z}_{\geq 0}$.

- Theorem 8.1** (a) *The above reduction rules are terminal and confluent.*
 (b) *Connected components of irreducible graphs are either isolated external vertices, \bullet , or $\bullet\text{---}\bullet$ or at least 3 external vertices connected to a single internal vertex.*

The termination of the above rules is obvious. The proof of confluence is left to the reader.

Corollary 8.2 *Irreducible graphs in \mathcal{G}_n are in 1–1 correspondence to partitions of $\{1, \dots, n\}$.*

The only irreducible graph with no external vertices is the empty graph \emptyset . Consequently, $R\mathcal{G}_0/\mathcal{R}(S_{kl}, S_l, k, l \geq 0, S_0)$ is a cyclic R -module generated by \emptyset . The projection $\mathcal{G}_0 \rightarrow R\mathcal{G}_0/\mathcal{R}(S_{kl}, k, l \geq 0, S_0) \simeq R$ followed by substitution

$$R \xrightarrow{p \rightarrow 1, s \rightarrow 1+q} \mathbb{Z}[q, v]$$

is the dichromatic polynomial of graphs. A generalization of dichromatic polynomial to ribbon graphs is considered by Bollobás and Riordan [6]. It can be defined by reductions rules similar to those above as well.

⁵ We did not check confluence for unoriented surfaces.

8.1 Partition category

Let R be a ring with a specified $\delta^{\pm 1} \in R$. A version of the “dichromatic” reduction rules appears in the context of the partition category. There are two types of that category: symmetric and planar one. In each of them, objects are non-negative integers.

In the symmetric partition category, the morphisms $[n] \rightarrow [m]$ are R -linear combinations of abstract graphs with $n + m$ external vertices divided into an *input set* and an *output set* of n and m vertices, respectively. Vertices in each of these sets are numbered. The internal vertices have valency at most 3. Furthermore, the graphs are subject to the following rules:

$$\begin{array}{lll}
 T_1: \text{graph} = \text{graph}, & T_2: \text{circle} = \delta, & T_3: \text{line} = \text{line}, \\
 T_4: \text{graph} = \text{graph}, & T_5: \text{line} = 1, & T_6: \text{dot-line} = \text{dot}, \\
 T_7: \text{graph} = \cup, & T_8: \text{graph} = \delta \downarrow.
 \end{array}$$

As before, empty/full dots represent internal/external vertices. The composition of morphisms $\Gamma_1 \in \text{Mor}([n], [m]), \Gamma_2 \in \text{Mor}([m], [k])$ is defined by identifying output vertices of Γ_1 with corresponding input vertices of Γ_2 . (The correspondence between these vertices is established by their numbering.) These vertices become internal in $\Gamma_2 \circ \Gamma_1$. The symmetric partition category is monoidal, with the tensor product of morphisms $\Gamma_1 \in \text{Mor}([n_1], [m_1]), \Gamma_2 \in \text{Mor}([n_2], [m_2])$ given by taking their disjoint union and shifting the numbering of the input and output vertices of Γ_2 by n_1 and m_1 respectively.

In the planar partition category, one thinks of objects as sets $[n] = \{\frac{1}{n+1}, \dots, \frac{n}{n+1}\} \subset [0, 1]$. Morphisms $[n] \rightarrow [m]$ are R -linear (manifold) graphs in $[0, 1] \times [0, 1]$ without S^1 's, whose external vertices are $[n] \times \{0\} \cup [m] \times \{1\}$. These graphs are considered up to relations T_1, \dots, T_8 . We denote the space of morphisms in the planar partition category by $\text{Mor}^P([n], [m])$. Compositions (respectively, tensor products) of morphisms are given by vertical (respectively, horizontal) stacking of graphs.

The importance of the planar (respectively, symmetric) partition category stems from the fact that the object $[1]$ is the universal Frobenius algebra (respectively, commutative Frobenius algebra) in a monoidal (respectively symmetric monoidal) category. Consequently, monoidal (respectively, symmetric monoidal) functors from the planar (respectively, symmetric) partition category into the category of R -modules are in 1–1 correspondence with Frobenius algebras (respectively, commutative Frobenius

algebras) over R . Furthermore, the algebra of morphisms $[n] \rightarrow [n]$ called the *partition algebra* appears in the theory of Potts models (see Jones [29] and Martin [40]).

Reduction relations going from left to right sides of equations $T_1 - T_8$ are locally confluent but not terminal since T_1 is invertible. (Nonetheless, we are going to prove that they are confluent.) The intuitive way of making these rules terminal is by allowing 4-valent vertices and by adding a reduction rule

$$\begin{array}{c} \diagup \quad \diagdown \\ \circ \quad \circ \\ \diagdown \quad \diagup \end{array} \longrightarrow \begin{array}{c} \diagdown \quad \diagup \\ \diagup \quad \diagdown \end{array}.$$

Now to make the new rules terminal and locally confluent one needs to add an additional relation involving 5-valent vertices, and then one involving 6-valent vertices, etc. Finally, one arrives at:

Theorem 8.3 (1) *The natural embedding of graphs of the symmetric partition category into (abstract) graphs factors to an isomorphism of R -modules*

$$\phi: \text{Mor}([n], [m]) \rightarrow \mathcal{G}_{n+m} / \mathcal{R}(\bar{S}_{k,l}, \bar{S}_l, \bar{S}_v, \bar{S}_{bw}, \bar{S}_{bwb}),$$

where

$$\begin{array}{l} \bar{S}_{k,l}: \left\{ \begin{array}{c} \diagup \quad \diagdown \\ \circ \quad \circ \\ \diagdown \quad \diagup \end{array} \right\} \rightarrow \begin{array}{c} \diagdown \quad \diagup \\ \diagup \quad \diagdown \end{array}, \quad \bar{S}_l: \left\{ \begin{array}{c} \diagup \quad \diagdown \\ \diagdown \quad \diagup \end{array} \right\} \rightarrow \delta \begin{array}{c} \diagdown \quad \diagup \\ \diagup \quad \diagdown \end{array}, \\ \bar{S}_v: \circ \rightarrow \emptyset, \quad \bar{S}_{bw}: \bullet \circ \rightarrow \bullet, \quad \bar{S}_{bwb}: \bullet \circ \bullet \rightarrow \bullet \bullet \bullet. \end{array}$$

(Note that these are the dichromatic reduction rules for $p = 0, q = v = w_1 = w_2 = 1, s = \delta$).

(2) *Similarly, the natural embedding of graphs of planar partition category into planar graphs in D^2 with $n + m$ external vertices factors to an isomorphism*

$$\phi^p: \text{Mor}^p([n], [m]) \rightarrow \mathcal{G}_{n+m}(D^2) / \mathcal{R}(\bar{S}_{k,l}, \bar{S}_l, \bar{S}_v, \bar{S}_{bw}, \bar{S}_{bwb}).$$

Sketch of Proof (1) The irreducible graphs in \mathcal{G}_{n+m} listed in Theorem 8.1 span $\mathcal{G}_{n+m} / \mathcal{R}(\bar{S}_{k,l}, \bar{S}_l, \bar{S}_v, \bar{S}_{bw}, \bar{S}_{bwb})$. Since all of these graphs are values of ϕ , it is an epimorphism. To prove that ϕ is 1-1 observe that connected components of every graph in $\text{Mor}([n], [m])$ determine a partition of $\{1, \dots, n + m\}$. Let $\text{Mor}^\tau([n], [m])$ be the subspace of $\text{Mor}([n], [m])$ spanned by graphs associated with the partition τ . Since T_1, \dots, T_8 preserve partitions,

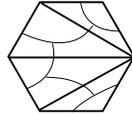
$$\text{Mor}([n], [m]) = \bigoplus_{\text{partitions } \tau} \text{Mor}^\tau([n], [m])$$

and, similarly, $\mathcal{G}_{n+m} / \mathcal{R}(\bar{S}_{k,l}, \bar{S}_l, \bar{S}_v, \bar{S}_{bw}, \bar{S}_{bwb})$ decomposes into subspaces indexed by partitions, which by Theorem 8.1 are 1-dimensional. Since ϕ preserves partition

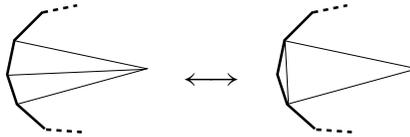
classes, it is enough to prove that $\text{Mor}^\tau([n], [m]) \simeq R$ as an R -module. This follows from the following:

Lemma 8.4 *Any two connected graphs with internal vertices of valency ≤ 3 are equivalent via relations T_1, \dots, T_8 .*

Proof T_4 and T_1 allow to “slide” edges past 2-valent and 3-valent vertices. Therefore, all cycles in a graph can be transformed into loops, which can be eliminated by T_2 and T_8 . Furthermore, all internal 1-valent vertices can be removed by T_5 , T_6 and T_7 . Consequently, each connected graph is equivalent to a tree with no internal 1-valent vertices. All such trees are related by T_1 moves. There is a geometric way to see that. First, any such tree embeds into D^2 and its dual corresponds to a division of a $(n + m)$ -gon into triangles by non-intersecting diagonals. Here is an example of a planar tree and the corresponding dual triangulation of 6-gon:



Any two such triangulations are related by the move:



which is dual to T_1 . □

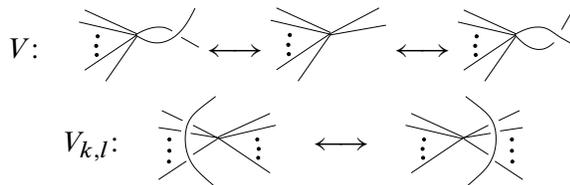
The proof of Theorem 8.3(2) is analogous. □

9 Application to knots

Now, we turn to spaces of dimension 3, which are the most difficult to deal with in the context of graph embeddings. Graphs in a 3-dimensional manifold M are the easiest to analyze if M is an I -bundle over a surface F , $I = [-1, 1]$, since then each graph is represented by its diagram in F and such representations are unique up to Reidemeister moves:

$$RI: \left(\begin{array}{c} | \\ \circlearrowleft \\ | \end{array} \right) \longleftrightarrow \left(\begin{array}{c} | \\ \circlearrowright \\ | \end{array} \right), \quad RII: \left(\begin{array}{c} \diagup \\ \diagdown \end{array} \right) \longleftrightarrow \left(\begin{array}{c} \diagdown \\ \diagup \end{array} \right) \left(\begin{array}{c} \diagup \\ \diagdown \end{array} \right) \left(\begin{array}{c} \diagdown \\ \diagup \end{array} \right), \quad \text{and} \quad RIII: \left(\begin{array}{c} \diagup \\ \diagdown \end{array} \right) \longleftrightarrow \left(\begin{array}{c} \diagdown \\ \diagup \end{array} \right)$$

and the moves



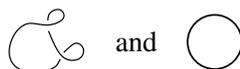
where there are k edges on the right and l on the left, for all $k, l \geq 0$.

The main problem in knot theory is deciding whether any two link diagrams represent isotopic links. This reduces now to question whether these link diagrams are equal in $\mathbb{Z}\mathcal{LD}(F)/\mathcal{R}(RI, RII, RIII)$, where $\mathcal{LD}(F)$ is the set of all link diagrams in F . (In classical knot theory $F = D^2$, but other surfaces are of interest for us as well.) Notice that this is a version of the problem formulated in Introduction.

The rules

$$r_1: \begin{array}{c} | \\ \circlearrowleft \\ | \end{array} \rightarrow \begin{array}{c} | \\ \circlearrowright \\ | \end{array}, \quad r_2: \begin{array}{c} \diagup \\ \diagdown \end{array} \rightarrow \begin{array}{c} \diagdown \\ \diagup \end{array} \left(\right.$$

although terminal are not confluent, since



are both irreducible but not equivalent to each other. However, it is easy to show by the method of Section 3.6 that r_1, r_2 together with

$$r'_1: \begin{array}{c} | \\ \circlearrowleft \\ | \end{array} \rightarrow \begin{array}{c} | \\ \circlearrowright \\ | \end{array}$$

are terminal and confluent. Unfortunately, the rule

$$r_3: \begin{array}{c} \diagup \\ \diagdown \end{array} \rightarrow \begin{array}{c} \diagdown \\ \diagup \end{array}$$

is not terminal since it is its own inverse. Furthermore, r_1, r'_1, r_2, r_3 are not confluent.

Nonetheless, inspired by the notion of confluence we ask the following question:

Question 9.1 For any given surface F , is there a set \mathcal{G} of graphs in F containing $\mathcal{LD}(F)$ and a finite set of terminal and confluent reduction rules S_1, \dots, S_d , with coefficients in a ring R such that the inclusion $\mathcal{LD}(F) \hookrightarrow \mathcal{G}$ induces a monomorphism

$$\phi: R\mathcal{LD}(F)/\mathcal{R}(RI, RII, RIII) \hookrightarrow R\mathcal{G}/\mathcal{R}(S_1, \dots, S_d).$$

A positive answer to this question would provide an obvious algorithm for distinguishing non-isotopic links in I -bundles over F . We conjecture that there does not exist a set of terminal and confluent reduction rules with these properties.

Confluence theory provides an immediate proof of the following statement.

Theorem 9.2 *Let F be any surface and $B \subset \partial F$ a finite set.*

- (1) *unoriented link diagrams (A_1 -webs) in F are invariant in $\mathbb{A}_1(F, B, R)$ under moves RII , $RIII$, and the first balanced Reidemeister move:*

$$Rlb: \left. \begin{array}{c} \circlearrowleft \\ \circlearrowright \end{array} \right\} \rightarrow \left. \begin{array}{c} \circlearrowright \\ \circlearrowleft \end{array} \right\}.$$

- (2) *A_2 -webs are invariant in $\mathbb{A}_2(F, B, R)$ under oriented 2nd and 3rd Reidemeister moves as well as oriented 1st balanced Reidemeister move and under moving an arc over a vertex.*
- (3) *Similarly, B_2 -webs and G_2 -webs in F are invariant under all 2nd and 3rd Reidemeister moves (involving both single and double lines) and under moving an arc over a vertex.*

To prove invariance under any of the above relations it is enough to check that reduction rules applied to both sides of that relation yield identical linear diagrams.

Corollary 9.3 *For orientable F , $\mathbb{A}_1(F, \emptyset, R)$, $\mathbb{B}_2(F, \emptyset, R)$, $\mathcal{G}_2(F, \emptyset, R)$, provide invariants of framed unoriented links and $\mathbb{A}_2(F, \emptyset, R)$ provides an invariant of framed oriented links under isotopy in $F \times I$.*

For $F = \mathbb{R}^2$, $B = \emptyset$, and $R = \mathbb{Z}[A^{\pm 1}]$, the module $\mathbb{A}_1(F, B, R)$ is free on one generator, \emptyset , and $[L] \in \mathbb{A}_1(F, B, R) = R$ is the Kauffman bracket of L , (see Kauffman [34]). For other oriented surfaces, $\mathbb{A}_1(F, \emptyset, R)$ is isomorphic to the Kauffman bracket skein module of $F \times I$ (see Hoste–Przytycki [25], Przytycki [50; 52] and Przytycki–Sikora [56]). (For more on Kauffman bracket skein modules see Bullock [7; 8], Bullock–Frohman–Kania-Bartoszyńska [9; 10], Blanchet–Habegger–Masbaum–Vogel [5], Bullock–Przytycki [11], Frohman–Gelca [15], Frohman–Gelca–Lofaro [16], Frohman–Kania-Bartoszyńska [17], Gelca–Sain [20; 19], Gilmer–Harris [21], Hoste–Przytycki [26; 27], Lê [38], Sallenave [59; 58], Sikora [60; 61], and Turaev [64].) Consequently, Corollary 4.1 immediately implies the result [52, Theorem 3.1] of Przytycki:

Theorem 9.4 *For any ring R with $A^{\pm 1} \in R$ and any orientable surface F , the Kauffman bracket skein module of $F \times [0, 1]$ is a free R -module with basis composed of links whose diagrams in F have no crossings and no contractible components.*

There are versions of this theorem for orientable I -bundles over non-orientable surfaces and for $B \neq \emptyset$. They can be easily proved by the method of confluence as well.

The module $\mathbb{A}_2(F, \emptyset, R)$ is isomorphic to the SU_3 -skein module of $F \times I$ introduced in Frohman–Zhong [18] and Sikora [62] (see also Ohtsuki–Yamada [46]). Consequently, Corollary 5.2 implies

Theorem 9.5 *The SU_3 -skein module of $F \times I$, $\mathcal{S}_3(F \times I, R)$ (in notation of [62]) is a free R -module with a basis given by all A_2 -webs in F with no 0-gons, no true bigons, and no true 4-gons.*

Problem 9.6 A large number of skein modules is considered in the literature, other than those mentioned above, Andersen–Turaev [1; 2], Gilmer–Zhong [22], Hadji–Morton [23], Hoste–Przytycki [24], Kaiser [32; 30; 31], Kalfgianni–Lin [33], Lieberum [39], Przytycki [48; 47; 49; 51; 54; 53; 55], Przytycki–Tsukamoto [57], Zhong [67] and Zhong–Lu [68]. Can the method of confluence be applied to determine canonical bases of these modules for $F \times I$?

The applications of confluence theory to knot theory discussed so far apply to links in I -bundles over surfaces. Unfortunately, reduction rules for links in arbitrary 3-manifolds are more difficult to handle. This is illustrated by the Kauffman bracket skein relations:

Let $\mathcal{L}(M)$ be the set of all framed unoriented links in an orientable 3-manifold M . Let R be a ring with a distinguished element $A^{\pm 1} \in R$ and let

$$S_1: \begin{array}{c} \diagup \\ \diagdown \end{array} \rightarrow A \left(\begin{array}{c} + \\ - \end{array} \right) \left(\begin{array}{c} \diagup \\ \diagdown \end{array} \right) \text{ and } S_2: \bigcirc \rightarrow -(A^2 + A^{-2})\emptyset$$

be reduction rules taking place in D^3 . The R -module $R\mathcal{L}(M)/\mathcal{R}(S_1, S_2)$ is called *the Kauffman bracket skein module of M* . We leave the proof of the following to the reader:

Proposition 9.7 *S_1, S_2 are confluent but not terminal.*

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