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Author(s): ANA PAULA S. DIAS and IAN STEWART

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# SYMMETRY GROUPOIDS AND ADMISSIBLE VECTOR FIELDS FOR COUPLED CELL NETWORKS

ANA PAULA S. DIAS AND IAN STEWART

## ABSTRACT

The space of admissible vector fields, consistent with the structure of a network of coupled dynamical systems, can be specified in terms of the network's symmetry groupoid. The symmetry groupoid also determines the robust patterns of synchrony in the network – those that arise because of the network topology. In particular, synchronous cells can be identified in a canonical manner to yield a quotient network. Admissible vector fields on the original network induce admissible vector fields on the quotient, and any dynamical state of such an induced vector field can be lifted to the original network, yielding an analogous state in which certain sets of cells are synchronized. In the paper, necessary and sufficient conditions are specified for *all* admissible vector fields on the quotient to lift in this manner. These conditions are combinatorial in nature, and the proof uses invariant theory for the symmetric group. Also the symmetry groupoid of a quotient is related to that of the original network, and it is shown that there is a close analogy with the usual normalizer symmetry that arises in group-equivariant dynamics.

## 1. Introduction

Coupled cell systems are finite sets of dynamical systems, called *cells*, which are coupled together. The topology or ‘architecture’ of the coupling is specified by a labelled graph or coupled cell network [5, 6, 17]. Such systems arise in many areas of applied science, including communication via the Internet, the spread of epidemics, food webs in ecosystems, metabolic networks in the cell, neural circuits, networks of gene expression, animal locomotion, commercial supply chains, electrical power grids, transport networks, and crowd flow.

Until recently the abstract theory of coupled cell systems has mainly focused on the effects of symmetry in the network [3–6] and the consequent formation of spatial and spatiotemporal patterns. The formal setting for this theory centres upon the symmetry group of the network.

The analysis of robust patterns of synchrony in general coupled cell systems – that is, dynamics in which sets of cells behave identically as a consequence of the network topology – has led to the fruitful notion of the ‘symmetry groupoid’ of a coupled cell network [17]. A groupoid is a generalization of a group, in which products of elements are not always defined; see Higgins [9]. The symmetry groupoid of a coupled cell network is a natural algebraic formalization of the ‘local symmetries’ that relate subsets of the network to each other. In particular, the ‘admissible’ vector fields – those specified by the network topology – are precisely those that are equivariant under the action of the symmetry groupoid.

Robust patterns of synchrony correspond to the existence of a ‘quotient’ network, in which synchronous cells are identified. One of the main theorems of [17] is that

if  $\phi: G \rightarrow \overline{G}$  is a quotient map of networks, then it induces a map  $\hat{\phi}$  between the spaces  $\mathcal{F}_G^P$  and  $\mathcal{F}_{\overline{G}}^{\overline{P}}$  of admissible vector fields on phase spaces  $P, \overline{P}$  for  $G, \overline{G}$ . Examples in that paper show that for some networks  $\hat{\phi}$  is surjective, but for others it is not. The surjectivity of  $\hat{\phi}$  is important because it determines whether all dynamics on  $\overline{G}$  lift to synchronous dynamics on  $G$ . The surjectivity problem for coupled cell networks asks for a characterization of those networks for which  $\hat{\phi}$  is surjective, and we solve that problem in this paper.

Specifically, our main result is Theorem 7.8, which gives necessary and sufficient conditions for any admissible vector field on a quotient network to lift to an admissible vector field on the original network. These conditions are combinatorial in nature, and are determined by groupoid-theoretic conditions on the network topology. The proofs are algebraic, and make essential use of elementary invariant theory for direct products of symmetric groups.

The analysis is motivated by an analogy between the symmetry group of a symmetric network and the symmetry groupoid of a general one. The analogous surjectivity problem for symmetric networks is intimately related to the existence (or not) of ‘hidden symmetries’ [16].

These arise in the following context. Suppose that a finite (or, more generally, compact Lie) group  $\Gamma$  acts linearly on a real vector space  $X$ . A smooth map  $f: X \rightarrow X$  is  $\Gamma$ -equivariant if

$$f(\gamma x) = \gamma f(x) \quad \forall x \in X, \gamma \in \Gamma.$$

If  $\Sigma$  is a subgroup of  $\Gamma$  then the *fixed-point subspace* of  $\Sigma$  is

$$\text{Fix}(\Sigma) = \{x \in X : \sigma x = x, \forall \sigma \in \Sigma\}.$$

It is well known and easy to prove that if  $f$  is  $\Gamma$ -equivariant then

$$f(\text{Fix}(\Sigma)) \subseteq \text{Fix}(\Sigma)$$

so we can form the restriction  $g = f|_{\text{Fix}(\Sigma)}$ . It is easy to show that  $g$  is equivariant under the natural action of  $N(\Sigma)/\Sigma$  on  $\text{Fix}(\Sigma)$ , where  $N(\Sigma)$  is the normalizer of  $\Sigma$  in  $\Gamma$ ; see [7, Exercise XIII.2.2]. However, normalizer equivariance does not always characterize the possible maps  $g$ . Extra conditions may be required, known as ‘hidden symmetries’. The statement that no hidden symmetries are present is equivalent to stating that every smooth  $N(\Sigma)/\Sigma$ -equivariant map on  $\text{Fix}(\Sigma)$  can be extended to a smooth  $\Gamma$ -equivariant map on  $X$ .

In Section 8 we show that the surjectivity problem for coupled cell networks is analogous to the hidden symmetry problem for symmetric networks. Associated with any quotient map of a coupled cell network  $G$  there is a subgroupoid  $\mathcal{S}$  of the groupoid  $\mathcal{B}_G$ , and a normalizer groupoid  $N(\mathcal{S})$ . The map  $\hat{\phi}: \mathcal{F}_G^P \rightarrow \mathcal{F}_{\overline{G}}^{\overline{P}}$  is surjective if and only if  $\overline{G}$  is the ‘natural’ quotient determined by  $\phi$  and the induced vector fields on  $\overline{G}$  are precisely the  $N(\mathcal{S})/\mathcal{S}$ -equivariant vector fields. Thus  $\hat{\phi}$  is surjective if and only if every smooth  $N(\mathcal{S})/\mathcal{S}$ -equivariant vector field on  $\overline{P}$  can be extended to a smooth  $\mathcal{B}_G$ -equivariant vector field on  $P$ . The space  $\overline{P}$  is closely analogous to the fixed-point space of a subgroup, and the analogy is sufficiently close that in effect there are no ‘hidden groupoid symmetries’ associated with  $\phi$ . However, we do not attempt to make this statement precise in this paper.

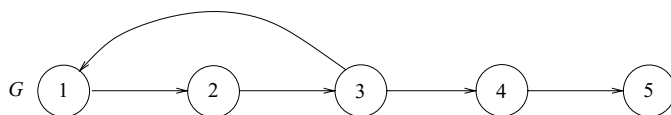


FIGURE 1. An example of a coupled cell graph  $G$ .

### 2. Coupled cell graphs

A coupled cell network can be represented schematically by a directed graph whose nodes correspond to cells and whose edges represent couplings, and for this reason we will employ the alternative name ‘coupled cell graph’. We start by defining what we mean by a coupled cell graph.

DEFINITION 2.1. A coupled cell graph  $G$  consists of the following.

- (a) A finite set  $\mathcal{C} = \{1, \dots, n\}$  of nodes (or cells).
- (b) A finite set of ordered pairs  $\mathcal{E} \subset \mathcal{C} \times \mathcal{C}$  of directed edges or arrows. If  $(a, b) \in \mathcal{E}$  then  $a$  is the tail and  $b$  is the head. An edge of the form  $(a, a)$  is internal. All other edges are external.
- (c) An equivalence relation  $\sim_{\mathcal{C}}$  on the nodes in  $\mathcal{C}$ .
- (d) An equivalence relation  $\sim_{\mathcal{E}}$  on the edges in  $\mathcal{E}$ .

We also assume that the following hold.

- (e)  $\{(c, c) : c \in \mathcal{C}\} \subset \mathcal{E}$ .
- (f) If  $(i, c) \sim_{\mathcal{E}} (j, d)$  then  $i \sim_{\mathcal{C}} j$  and  $c \sim_{\mathcal{C}} d$ .
- (g)  $(c, c) \sim_{\mathcal{E}} (d, d')$  if and only if  $d = d'$  and  $d \sim_{\mathcal{C}} c$ .

We write  $G = (\mathcal{C}, \mathcal{E}, \sim_{\mathcal{C}}, \sim_{\mathcal{E}})$ , and refer to  $G$  as a ‘graph’.

The diagram  $\text{Diag}(G)$  of  $G$  is constructed in the following way: for each  $\sim_{\mathcal{C}}$ -equivalence class of nodes we choose a distinct node symbol; for each  $\sim_{\mathcal{E}}$ -equivalence class of external edges we choose a distinct arrow.

Definition 2.1(f) implies that arrows between nodes can be identical only when the nodes at the heads are identical and the nodes at the tails are identical. Node symbols can be interpreted as arrows from a node to itself – that is, internal edges. Condition (g) implies that an internal edge cannot be equivalent to an external edge.

EXAMPLE 2.2. (a) Figure 1 shows a graph  $G = (\mathcal{C}, \mathcal{E}, \sim_{\mathcal{C}}, \sim_{\mathcal{E}})$ , where the following hold.

- (i)  $\mathcal{C} = \{1, 2, 3, 4, 5\}$ .
- (ii)  $\mathcal{E} = \{(1, 1), (2, 2), (3, 3), (4, 4), (5, 5), (1, 2), (2, 3), (3, 4), (4, 5), (3, 1)\}$ .
- (iii)  $\sim_{\mathcal{C}}$ -equivalence class:  $\{1, 2, 3, 4, 5\}$ .
- (iv)  $\sim_{\mathcal{E}}$ -equivalence classes:  $\{(1, 1), (2, 2), (3, 3), (4, 4), (5, 5)\}$ ,  $\{(1, 2), (2, 3), (3, 4), (4, 5), (3, 1)\}$ .

(b) Figure 2 shows a graph  $G = (\mathcal{C}, \mathcal{E}, \sim_{\mathcal{C}}, \sim_{\mathcal{E}})$ , where the following hold.

- (i)  $\mathcal{C} = \{1, 2, 3, 4\}$ .
- (ii)  $\mathcal{E} = \{(1, 1), (2, 2), (3, 3), (4, 4), (1, 2), (1, 3), (2, 3), (4, 2), (4, 3)\}$ .
- (iii)  $\sim_{\mathcal{C}}$ -equivalence classes:  $\{1, 4\}, \{2, 3\}$ .
- (iv)  $\sim_{\mathcal{E}}$ -equivalence classes:  $\{(1, 1), (4, 4)\}, \{(2, 2), (3, 3)\}, \{(1, 2), (4, 3)\}, \{(1, 3), (4, 2)\}, \{(2, 3)\}$ .

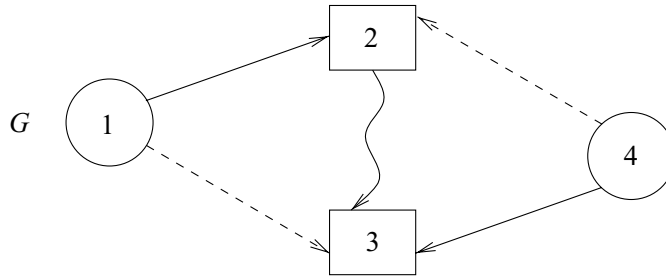


FIGURE 2. An example of a coupled cell graph  $G$ .

### 3. Symmetry groupoids

Given a graph  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  as in Definition 2.1, we can define the ‘symmetry groupoid’  $\mathcal{B}_G$  of  $G$ . This definition is tailored to the dynamics of the network, and centres upon the notion of an ‘input set’. We start by reviewing some basic properties of groupoids; see Higgins [9] and the sketch in Brown [2].

#### 3.1. Groupoids

A groupoid is a special kind of category, so we begin by defining a category, see MacLane [12] and Herrlich and Stricker [8]. There are several equivalent formalizations of this concept. In this paper, a category  $\mathcal{G}$  consists of

- (a) a collection  $\mathcal{O}$  of objects  $a, b, \dots$ ;
- (b) a family of disjoint sets  $G(a, b)$ , one for each pair  $(a, b)$  of objects;
- (c) a distinguished element  $\epsilon_a$  of  $G(a, a)$  for each  $a$ ;
- (d) a law of composition: if  $\theta \in G(a, b)$  and  $\phi \in G(b, c)$ , then  $\phi\theta \in G(a, c)$ ; otherwise  $\phi\theta$  is not defined.

In addition we require two axioms.

- (1) Associativity: If  $\theta \in G(a, b)$ ,  $\phi \in G(b, c)$  and  $\psi \in G(c, d)$ , then  $\psi(\phi\theta) = (\psi\phi)\theta$ .
- (2) Identity: If  $\theta \in G(a, b)$  then  $\theta\epsilon_a = \epsilon_b\theta$ .

A category is *small* if its objects form a set. The members of  $G(a, b)$  are called  $\mathcal{G}$ -maps or  $\mathcal{G}$ -morphisms from  $a$  to  $b$ . The element  $\epsilon_a$  is called the *identity morphism* on  $G(a, a)$ . A *groupoid* is a small category  $\mathcal{G}$  consisting of objects and  $\mathcal{G}$ -morphisms, with the property that every  $\mathcal{G}$ -morphism has an inverse in  $\mathcal{G}$ . A groupoid  $\mathcal{G}$  is *connected* if  $G(a, b) \neq \emptyset$  for all objects  $a, b$  of  $\mathcal{G}$ . A *subgroupoid*  $\mathcal{S}$  of a groupoid  $\mathcal{G}$  is a subset of  $\mathcal{G}$  that is closed under products (when defined) and taking the inverses. The *components* of a groupoid are its maximal connected subgroupoids. A groupoid is the disjoint union of its components [9, Proposition 6, p. 27].

#### 3.2. Symmetry groupoid of a coupled cell graph

Let  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  be a graph in the sense of Definition 2.1.

Define the *input set*  $I(c)$  of a node  $c$  to be

$$I(c) = \{i \in \mathcal{C} : (i, c) \in \mathcal{E}\}.$$

Since we are assuming that  $\{(c, c) : c \in \mathcal{C}\} \subset \mathcal{E}$  then we always have  $c \in I(c)$ .

Given  $c, d \in \mathcal{C}$ , if there is a bijection  $\beta$  from  $I(c)$  to  $I(d)$  such that  $\beta(c) = d$  and for all  $i \in I(c)$  we have  $(i, c) \sim_E (\beta(i), d)$ , then we call  $\beta$  an *input isomorphism*

from cell  $c$  to cell  $d$ . In that case we say that  $c \sim_I d$ . Thus  $\sim_I$  is another equivalence relation on  $\mathcal{C}$ , which we call *input equivalence*. Moreover, it refines  $\sim_{\mathcal{C}}$ .

It will clarify the exposition if we adopt a slightly more formal approach than that employed in [17]. We define

$$B(c, d) = \{(\beta, c, d) : \beta \text{ is an input isomorphism from } c \text{ to } d\}.$$

Observe that  $B(c, d) \neq \emptyset$  if and only if  $c \sim_I d$ . As well as  $\beta$ , we include the head  $c$  and tail  $d$  in the formal definition of  $B(c, d)$ , to make those cells explicit. By doing this we ensure that  $B(c, d)$  and  $B(c', d')$  are disjoint for distinct pairs  $(c, d)$  and  $(c', d')$ . This is done implicitly in [17, Remark 3.6]. Our notation deviates from that of [17] in this respect.

EXAMPLE 3.1. We return to Example 2.2(a). Since  $I(1) = \{1, 3\}$  and  $I(2) = \{2, 1\}$ , then  $\beta_{12} : I(1) \rightarrow I(2)$  such that  $\beta_{12}(1) = 2, \beta_{12}(3) = 1$  is an input isomorphism from cell 1 to cell 2. In fact  $B(1, 2) = \{(\beta_{12}, 1, 2)\}$ . Also  $B(1, 1) = \{(\text{id}_{\{1,3\}}, 1, 1)\}$ .

We use  $\dot{\cup}$  for disjoint union. Consider now

$$\mathcal{B}_G = \dot{\bigcup}_{c,d \in \mathcal{C}} B(c, d)$$

and define a product operation on  $\mathcal{B}_G$ . Elements  $(\beta_2, c, d) \in B(c, d)$  and  $(\beta_1, a, b) \in B(a, b)$  can be multiplied only when  $b = c$ , and in this case we define

$$(\beta_2, b, d)(\beta_1, a, b) = (\beta_2\beta_1, a, d) \in B(a, d) \tag{3.1}$$

where  $\beta_2\beta_1$  denotes the usual composition of functions.

THEOREM 3.2.  $\mathcal{B}_G$  is a groupoid whose objects are the nodes of  $G$ , and the  $\mathcal{B}_G$ -morphisms are the elements of the sets  $B(c, d)$ . The product operation between the morphisms is as defined in (3.1).

Proof. See [17, Definition 3.5]. For consistency with our notation, note that  $\epsilon_c = (\text{id}_{I(c)}, c, c)$  is the identity element of  $B(c, c)$ . Also the inverse of  $(\beta, a, b) \in B(a, b)$  is  $(\beta^{-1}, b, a) \in B(b, a)$ .  $\square$

Following [17], we call  $\mathcal{B}_G$  the *symmetry groupoid* of the graph  $G$ . For any  $c \in \mathcal{C}$ , the set  $B(c, c)$  is a group, called the *vertex group* corresponding to  $c$ .

REMARK 3.3. The components of  $\mathcal{B}_G$  are in one-to-one correspondence with the  $\sim_I$ -equivalence classes on  $\mathcal{C}$  (and each component is a subgroupoid of  $\mathcal{B}_G$ ). More precisely, if  $\mathcal{A} \subseteq \mathcal{C}$  is an  $\sim_I$ -equivalence class, then  $\dot{\bigcup}_{c,d \in \mathcal{A}} B(c, d)$  is a component of  $\mathcal{B}_G$ . We say that  $c, d \in \mathcal{C}$  are *in the same (connected) component* of  $\mathcal{B}_G$  if and only if  $c \sim_I d$ .

### 3.3. Structure of $B(c, d)$

Let  $B(c, d) \subset \mathcal{B}_G$ . We can specify the structure of the set

$$B'(c, d) = \{\beta : (\beta, c, d) \in B(c, d)\}$$

in terms of the structure of  $G$ . To simplify notation we write  $B(c, d)$  instead of  $B'(c, d)$ . We can distinguish the following three cases.

- (1) If  $c \not\sim_I d$  then  $B(c, d) = \emptyset$ .
- (2) If  $c = d$  we can define an equivalence relation  $\equiv_c$  on  $I(c)$  by

$$j_1 \equiv_c j_2 \iff (j_1, c) \sim_E (j_2, c).$$

If  $K_1 = \{c\}, K_2, \dots, K_{r(c)}$  are the  $\equiv_c$ -equivalence classes (on  $I(c)$ ), then

$$B(c, c) = \mathbf{S}_{K_2} \times \dots \times \mathbf{S}_{K_{r(c)}}, \tag{3.2}$$

where each  $\mathbf{S}_{K_i}$  comprises all permutations of the set  $K_i$ , extended by the identity on  $I(c) \setminus K_i$ .

- (3) If  $c \neq d$  and  $c \sim_I d$  (and so  $B(c, d) \neq \emptyset$ ), then for any  $\beta \in B(c, d)$  we have

$$B(c, d) = \beta B(c, c) = B(d, d)\beta.$$

#### 4. Coupled cell systems

We now make precise the connection between coupled cell systems and coupled cell graphs. Recall that a coupled cell system is a network of dynamical systems coupled together. We represent such a system by a labelled directed graph  $G$  (that is, a coupled cell graph in the sense of Definition 2.1), whose nodes correspond to *cells*, and whose edges represent *couplings*. The term ‘coupling’ here is used in the sense that the output of certain cells affects the time-evolution of other cells.

##### 4.1. Coupled cell systems and coupled cell graphs

Again, we follow the treatment in [17]. Consider a coupled cell graph  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  with symmetry groupoid  $\mathcal{B}_G$ . We now define a space of vector fields associated with  $G$ . We say that these vector fields have symmetry groupoid  $\mathcal{B}_G$ . They are the vector fields that are compatible with the labelled graph structure.

Specifically, to each cell  $c \in \mathcal{C}$  we associate a *cell phase space*  $P_c$ , which for simplicity we assume is a non-zero finite-dimensional real vector space. The basic theory extends to the case when  $P_c$  is a smooth manifold, but the more sophisticated questions have not yet been explored in that generality.

If  $c, d$  are in the same  $\sim_C$ -equivalence class, then we suppose that  $P_c = P_d$  and identify these spaces canonically. The *total phase space* is

$$P = \prod_{c \in \mathcal{C}} P_c$$

with coordinate system

$$x = (x_c)_{c \in \mathcal{C}}$$

on  $P$ . If  $\mathcal{D}$  is any subset of  $\mathcal{C}$  we define

$$P_{\mathcal{D}} = \prod_{c \in \mathcal{D}} P_c$$

and if  $\pi_{\mathcal{D}} : P \rightarrow P_{\mathcal{D}}$  denotes the natural projection then

$$x_{\mathcal{D}} = \pi_{\mathcal{D}}(x).$$

Suppose that  $\mathcal{D}_1, \mathcal{D}_2$  are subsets of  $\mathcal{C}$  and that there is a bijection  $\beta : \mathcal{D}_1 \rightarrow \mathcal{D}_2$  preserving  $\sim_C$ -equivalence classes. Define the *pullback map*

$$\beta^* : P_{\mathcal{D}_2} \rightarrow P_{\mathcal{D}_1}$$

by

$$(\beta^*(z))_j = z_{\beta(j)} \quad \forall j \in \mathcal{D}_1, z \in P_{\mathcal{D}_2}.$$

Suppose that  $c \sim_I d$ . If  $x_{I(c)} = (x_c, x_{i_1}, \dots, x_{i_r})$  and  $\beta \in B(c, d)$ ; then  $\beta^*(x_{I(d)}) = (x_d, x_{\beta(i_1)}, \dots, x_{\beta(i_r)})$ .

The class of vector fields determined by  $G$  is defined as follows.

DEFINITION 4.1. A (smooth) vector field  $f: P \rightarrow P$  is  $\mathcal{B}_G$ -equivariant or  $G$ -admissible if the following hold.

(a) For any  $c \in \mathcal{C}$  the component  $f_c$  depends only on  $x_{I(c)}$ . By abuse of notation we write  $f_c(x) = f_c(x_{I(c)})$  to make this restriction on  $f_c$  explicit.

(b) For all  $c, d \in \mathcal{C}$  and  $\beta \in B(c, d)$  (so that in particular  $d = \beta(c)$ )

$$f_d(x_{I(d)}) = f_c(\beta^*(x_{I(d)})) \quad \forall x \in P$$

or, less explicitly,

$$f_d(x) = f_c(\beta^*(x)).$$

We say that  $f_c: P_{I(c)} \rightarrow P_c$  is  $B(c, c)$ -invariant if

$$f_c(\beta^*(x_{I(c)})) = f_c(x_{I(c)}) \quad \forall x \in P$$

for all  $\beta \in B(c, c)$ . This property is the same as the usual invariance property under a group, if we consider  $B(c, c)$  as acting on  $P_{I(c)}$  by permutation of the indices in  $I(c)$  (recall (3.2)).  $\mathcal{B}_G$ -equivariant maps can be specified in terms of  $B(c, c)$ -invariants,

THEOREM 4.2. A vector field  $f: P \rightarrow P$  is  $\mathcal{B}_G$ -equivariant if and only if for each connected component  $\mathcal{Q}$  of  $\mathcal{B}_G$  the following hold

(a)  $f_c$  is  $B(c, c)$ -invariant for some  $c \in \mathcal{Q}$ .

(b) For  $d \in \mathcal{Q}$  such that  $d \neq c$ , given (any)  $\beta \in B(c, d)$ , we have

$$f_d(x_{I(d)}) = f_c(\beta^*(x_{I(d)})).$$

Proof. See [17, Lemma 4.5]. □

DEFINITION 4.3. For a given choice of the  $P_c$  we define  $\mathcal{F}_G^P$  to consist of all smooth admissible vector fields on  $P$ . Clearly  $\mathcal{F}_G^P$  is a vector space over  $\mathbf{R}$ . Like all function spaces, it can be equipped with a variety of topologies, but here only the vector space structure is relevant.

EXAMPLE 4.4. In Example 2.2(a),  $\mathcal{B}_G$  is connected. All the vertex groups  $B(i, i)$  consist only of the identity element  $\epsilon_i = (\text{id}_{I(i)}, i, i)$ . Moreover, if  $\beta_{ij}: I(i) = \{i, i_1\} \rightarrow I(j) = \{j, j_1\}$  denotes the isomorphism for which  $\beta_{ij}(i) = j$  and  $\beta_{ij}(i_1) = j_1$ , then  $B(i, j) = \{(\beta_{ij}, i, j)\}$ . If  $P_1$  corresponds to the phase space of cell 1, then the total phase space is  $P = P_1^5$  since all the cells are identical. Using Theorem 4.2, given any  $f_1: P_{I(1)} \rightarrow P_1$ , and setting  $x_{I(1)} = (x_1, x_3)$ , the  $\mathcal{B}_G$ -equivariance condition takes the form

$$f_j(x_j, x_{j_1}) = f_1(x_{\beta_{1j}(1)}, x_{\beta_{1j}(3)})$$



for  $j = 2, \dots, 5$ . In other words, any  $\mathcal{B}_G$ -equivariant vector field  $f : P \rightarrow P$  has the form

$$f(x_1, x_2, x_3, x_4, x_5) = (f_1(x_1, x_3), f_1(x_2, x_1), f_1(x_3, x_2), f_1(x_4, x_3), f_1(x_5, x_4)).$$

### 5. Balanced equivalence relations and quotients

As explained in [17], synchrony in coupled cell systems may be a consequence of features that depend only on the given network architecture. That is, they are valid for any admissible vector field associated with a given coupled cell graph. Thus the possibility of dynamical synchrony is related to purely combinatorial features of the network. To describe these features, we introduce the notion of a balanced equivalence relation  $\bowtie$  on the nodes  $\mathcal{C}$ . Such equivalence relations can force the existence of certain flow-invariant spaces  $\Delta_{\bowtie}$  for all  $f \in \mathcal{F}_G^P$  in which certain subsets of cells (the  $\bowtie$ -equivalence classes) are synchronous. Moreover, the restriction of any  $f$  to  $\Delta_{\bowtie}$  defines a new vector field associated with a new *quotient* coupled cell graph.

#### 5.1. Balanced equivalence relations

An equivalence relation  $\bowtie$  on  $\mathcal{C}$  is *balanced* if for all  $c, d \in \mathcal{C}$  with  $c \bowtie d$  and  $c \neq d$ , there exists  $\gamma \in B(c, d)$  such that  $i \bowtie \gamma(i)$  for all  $i \in I(c)$ . Define the *polydiagonal subspace*

$$\Delta_{\bowtie} = \{x \in P : x_c = x_d \text{ whenever } c \bowtie d, \forall c, d \in \mathcal{C}\}$$

which is a vector subspace of  $P$ .

REMARK 5.1. A balanced equivalence relation refines  $\sim_I$ . That is, if  $c \bowtie d$  then  $c \sim_I d$ .

THEOREM 5.2. For any choice of total phase space  $P$ , an equivalence relation  $\bowtie$  on  $\mathcal{C}$  satisfies

$$f(\Delta_{\bowtie}) \subseteq \Delta_{\bowtie} \quad \forall f \in \mathcal{F}_G^P$$

if and only if  $\bowtie$  is balanced.

*Proof.* See [17, Theorem 6.5], where  $\bowtie$  is said to be ‘robustly polysynchronous’ if the above condition on  $\Delta_{\bowtie}$  holds. □

#### 5.2. Quotient maps

Quotient maps are a way to identify synchronous cells in a coupled cell system, while preserving the dynamics.

DEFINITION 5.3. Let  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  and  $\overline{G} = (\overline{\mathcal{C}}, \overline{\mathcal{E}}, \sim_{\overline{\mathcal{C}}}, \sim_{\overline{E}})$  be coupled cell graphs. A map  $\phi : \mathcal{C} \rightarrow \overline{\mathcal{C}}$  is a *quotient map* from  $G$  to  $\overline{G}$  if the following hold.

- (a)  $\phi$  is surjective.
- (b) Input arrows lift: If  $\overline{c} = \phi(c)$ , then  $\phi$  maps  $I(c)$  surjectively onto  $I(\overline{c})$ .
- (c) Input isomorphisms lift: Let  $d, d' \in \overline{\mathcal{C}}$  such that there exists  $\overline{\beta} \in \overline{B}(d, d')$ . Choose  $c, c' \in \mathcal{C}$  such that  $\phi(c) = d$  and  $\phi(c') = d'$ . Then there exists  $\beta \in B(c, c')$  such that  $\overline{\beta}(\phi(i)) = \phi(\beta(i))$  for all  $i \in I(c)$ .

(This is [17, Definition 8.1].)

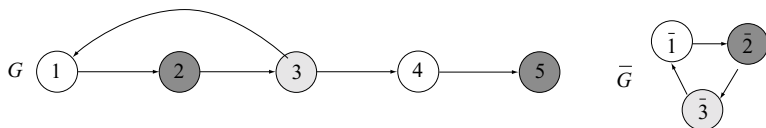


FIGURE 3. A coupled cell graph  $G$  and the corresponding quotient graph  $\bar{G} = G / \bowtie$  given by the balanced equivalence relation  $\bowtie$  with classes  $\{1, 4\}$ ,  $\{2, 5\}$  and  $\{3\}$ .

REMARK 5.4. Given a quotient map  $\phi : \mathcal{C} \rightarrow \bar{\mathcal{C}}$  between the two graphs, then the relation  $\bowtie$  (more specifically,  $\bowtie_\phi$ ) defined by

$$c \bowtie c' \iff \phi(c) = \phi(c')$$

is a balanced equivalence relation [17, Lemma 8.2(c)]. Thus by Theorem 5.2 we have  $f(\Delta_{\bowtie}) \subseteq \Delta_{\bowtie}$  for all  $f \in \mathcal{F}_G^P$ .

5.3. The natural quotient

Let  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  be a coupled cell graph and  $\bowtie$  a balanced equivalence relation on  $\mathcal{C}$ . Following [17, Section 7] we construct a coupled cell graph  $\bar{G} = G / \bowtie$  called the ‘natural quotient’ of  $G$  by  $\bowtie$ , whose cells are the equivalence classes  $\bar{c}$  of  $\bowtie$ . Moreover,  $\bar{G}$  is a quotient of  $G$ , and is universal among such quotients. That is, non-isomorphic quotient graphs can correspond to the same balanced equivalence relation, but they can all be obtained from the natural quotient by leaving cells unchanged but refining the relation  $\sim_{\bar{E}}$  of edge-equivalence.

Consider  $\phi : \mathcal{C} \rightarrow \bar{\mathcal{C}}$  such that  $\phi(c) = \bar{c}$  where  $\bar{c}$  denotes the  $\bowtie$ -equivalence class of the cell  $c \in \mathcal{C}$ . Now  $\bar{G} = (\bar{\mathcal{C}}, \bar{\mathcal{E}}, \sim_{\bar{C}}, \sim_{\bar{E}})$  is defined by the following.

- (1)  $\bar{\mathcal{C}} = \{\bar{c} : c \in \mathcal{C}\}$ .
- (2)  $\bar{c} \sim_{\bar{C}} \bar{d} \iff c \sim_C d$ .
- (3)  $\bar{\mathcal{E}} = \{(\bar{i}, \bar{c}) : (i, c) \in \mathcal{E}, i \not\bowtie c\} \cup \{(\bar{c}, \bar{c}) : c \in \mathcal{C}\}$ .
- (4) If  $(j, d) \in \bar{\mathcal{E}}$  and  $c \in \mathcal{C}$  is such that  $\bar{c} = d$ , define

$$\Omega_c(j) = \{i \in I(c) : \bar{i} = j\}.$$

Given  $(j_1, d_1), (j_2, d_2) \in \bar{\mathcal{E}}$  then

$$(j_1, d_1) \sim_{\bar{E}} (j_2, d_2) \tag{5.1}$$

if and only if for some  $c_1, c_2 \in \mathcal{C}$  such that  $\bar{c}_1 = d_1, \bar{c}_2 = d_2$  there exists  $\gamma \in B(c_1, c_2)$  such that

$$\gamma(\Omega_{c_1}(j_1)) = \Omega_{c_2}(j_2).$$

This definition does not depend on the choice of  $c_1, c_2$ .

THEOREM 5.5. The above map  $\phi$  is a quotient map between  $G$  and  $\bar{G}$ . Moreover, it is universal.

Proof. See [17, Theorems 8.3 and 8.4]. □

EXAMPLE 5.6. Figure 3 shows the graph  $G$  from Example 2.2(a), with the balanced equivalence relation on  $\mathcal{C}$  with classes

$$\{1, 4\}, \{2, 5\}, \{3\}.$$

We obtain the quotient graph  $\overline{G} = G / \bowtie = (\overline{\mathcal{C}}, \overline{\mathcal{E}}, \sim_{\overline{\mathcal{C}}}, \sim_{\overline{E}})$ , where the following hold.

- (i)  $\overline{\mathcal{C}} = \{\overline{1}, \overline{2}, \overline{3}\}$ .
- (ii)  $\overline{\mathcal{E}} = \{(\overline{1}, \overline{1}), (\overline{2}, \overline{2}), (\overline{3}, \overline{3}), (\overline{1}, \overline{2}), (\overline{2}, \overline{3}), (\overline{3}, \overline{1})\}$ .
- (iii)  $\sim_{\overline{\mathcal{C}}}$ -equivalence class:  $\{\overline{1}, \overline{2}, \overline{3}\}$ .
- (iv)  $\sim_{\overline{E}}$ -equivalence classes:  $\{(\overline{1}, \overline{1}), (\overline{2}, \overline{2}), (\overline{3}, \overline{3})\}, \{(\overline{1}, \overline{2}), (\overline{2}, \overline{3}), (\overline{3}, \overline{1})\}$ .

### 6. Induced vector fields

In [17] it is shown that any quotient map  $\phi : G \rightarrow \overline{G}$  converts  $G$ -admissible vector fields into  $\overline{G}$ -admissible vector fields in a natural way. We present this procedure formally in the case when  $\phi : G \rightarrow G / \bowtie$  is the natural quotient constructed in Subsection 5.3. We also illustrate this construction with some examples, which are useful as motivation for our main theorem.

#### 6.1. Induced vector fields are admissible

Let  $G$  be a coupled cell graph and let  $\bowtie$  be a balanced equivalence relation on  $\mathcal{C}$ . Let  $\overline{G} = G / \bowtie$  and consider  $\phi : G \rightarrow \overline{G}$  as in Subsection 5.3. Recall that  $f(\Delta_{\bowtie}) \subseteq \Delta_{\bowtie}$  for all admissible vector fields  $f \in \mathcal{F}_G^P$  by Theorem 5.2.

Having chosen the cell phase spaces  $P_c$  for  $c \in \mathcal{C}$ , then for each  $\overline{c} \in \overline{\mathcal{C}}$  we define the corresponding cell phase space to be

$$\overline{P}_{\overline{c}} = P_c.$$

If we choose a set of representatives  $\mathcal{R}$  for  $\phi$  (one for each  $\bowtie$ -equivalence class) we define

$$\overline{P} = \prod_{c \in \mathcal{R}} \overline{P}_{\overline{c}} = \prod_{c \in \mathcal{R}} P_c$$

to be the total phase space for  $\overline{G}$ . If  $x = (x_c)_{c \in \mathcal{C}}$  are coordinates on  $P$ , we can consider  $y = (y_{\overline{c}})_{\overline{c} \in \overline{\mathcal{C}}}$  as coordinates on  $\overline{P}$ . In other words, each cell  $\overline{c}$  of  $G / \bowtie$  inherits the phase space of any (hence every) cell that lies in the  $\bowtie$ -equivalence class  $\overline{c}$ .

Now define an injective map  $\alpha : \overline{P} \rightarrow P$  by

$$(\alpha(y))_c = y_{\overline{c}} \quad \forall c \in \mathcal{C}, y \in \overline{P}.$$

Note that  $\Delta_{\bowtie} = \alpha(\overline{P})$ . Since  $f(\Delta_{\bowtie}) \subseteq \Delta_{\bowtie}$ , for all  $f \in \mathcal{F}_G^P$ , then as in [17] we may define

$$\begin{aligned} \overline{f} : \overline{P} &\longrightarrow \overline{P} \\ y &\longmapsto \alpha^{-1}(f(\alpha(y))) \end{aligned}$$

and  $\overline{f}$  is called the *induced vector field* corresponding to  $f$ . That is,  $\overline{f}$  is the projection by  $\alpha^{-1}$  onto  $\overline{P}$  of  $f$  restricted to  $\Delta_{\bowtie}$ .

**THEOREM 6.1.** *For any  $f \in \mathcal{F}_G^P$ , the induced vector field  $\overline{f} \in \mathcal{F}_{\overline{G}}^{\overline{P}}$ . In another words, the function*

$$\hat{\phi} : \begin{array}{ccc} \mathcal{F}_G^P & \longrightarrow & \mathcal{F}_{\overline{G}}^{\overline{P}} \\ f & \longmapsto & \overline{f} \end{array}$$

is well defined.

*Proof.* See [17, Theorem 9.2]. □

In [17] it is observed that  $\hat{\phi}$  is surjective for some graphs, but not for others. The aim of this paper is to find necessary and sufficient conditions for the map  $\hat{\phi}$  to be surjective. It is never surjective if  $\bar{G}$  is not the natural quotient, by [17, Corollary 8.8], so without loss of generality we may assume that  $\bar{G} = G / \bowtie$ . The dynamics of  $f$  on  $P$  and those of  $\bar{f}$  on  $\bar{P}$  are related. It is shown in [17] that any state of  $\bar{f}$  ‘lifts’ to a corresponding state of  $f$  in which all  $\bowtie$ -equivalent cells are synchronous. The question we now address is: given any vector field  $\bar{f}$  in  $\mathcal{F}_{\bar{G}}^{\bar{P}}$ , is there always a vector field  $f$  in  $\mathcal{F}_G^P$  which, when restricted to the polydiagonal  $\Delta_{\bowtie}$ , coincides with  $\bar{f}$ ? We show (Theorem 7.8) that two combinatorial conditions are needed in order for  $\hat{\phi}$  to be surjective.

### 6.2. Examples

We give some examples of graphs  $G$  and balanced equivalence relations to illustrate some situations where the map  $\hat{\phi}$  is surjective, and others where it is not. These examples motivate all of our subsequent analysis.

EXAMPLE 6.2. Consider the graph  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  of Figure 4 where the following hold.

- (i)  $\mathcal{C} = \{1, 2, 3, 4, c\}$ .
- (ii)  $\mathcal{E} = \{(1, 1), (2, 2), (3, 3), (4, 4), (c, c), (1, c), (2, c), (3, c), (4, c)\}$ .
- (iii)  $\sim_C$ -equivalence class:  $\{1, 2, 3, 4, c\}$ .
- (iv)  $\sim_E$ -equivalence classes:  $\{(1, 1), (2, 2), (3, 3), (4, 4), (c, c)\}, \{(1, c), (2, c), (3, c), (4, c)\}$ .

Suppose for simplicity that  $P = \mathbf{R}^5$ . (Similar considerations apply if  $P = \mathbf{R}^{5k}$  for  $k > 1$ , but the calculations are more complicated.) Any admissible vector field  $f \in \mathcal{F}_G^P$  has the form

$$f(x) = (f_1(x_1), f_1(x_2), f_1(x_3), f_1(x_4), f_c(x_c, \overline{x_1, x_2, x_3, x_4}))$$

where  $\overline{x_1, x_2, x_3, x_4}$  means that  $f_c$  is invariant under the permutations of the corresponding  $x_i$ . That is, it is a symmetric function of those  $x_i$  [11]. Observe that for this example,  $B(1, 2) = \{(\beta, 1, 2)\}$  where  $\beta: I(1) = \{1\} \rightarrow I(2) = \{2\}$ . The map  $\beta$  satisfies  $\beta(1) = 2$ , and is an input isomorphism since  $(1, 1) \sim_E (2, 2)$  (which is

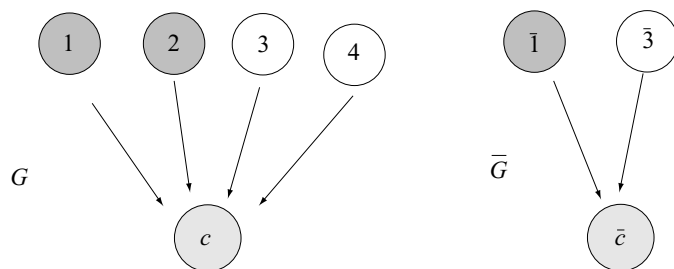


FIGURE 4. A coupled cell graph  $G$  and the corresponding quotient graph  $\bar{G}$  given by the  $\bowtie$ -equivalence relation with classes  $\{1, 2\}$ ,  $\{3, 4\}$  and  $\{c\}$ .

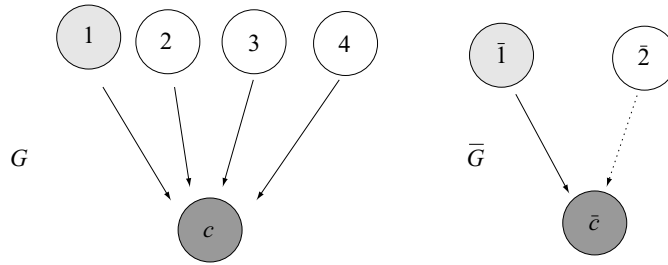


FIGURE 5. A coupled cell graph  $G$  and the corresponding natural quotient graph  $\bar{G}$  given by the equivalence relation  $\bowtie$  with classes  $\{1\}$ ,  $\{2, 3, 4\}$  and  $\{c\}$ .

equivalent to  $1 \sim_C 2$ ). Thus  $\mathcal{B}_G$ -equivariance implies that  $f_2(x_2) = f_1(x_2)$ . Similarly for  $f_3, f_4$ .

(a) Consider the (balanced) equivalence relation  $\bowtie$  on  $\mathcal{C}$  with classes

$$\{1, 2\}, \{3, 4\}, \{c\}$$

and let  $\bar{G} = (\bar{\mathcal{C}}, \bar{\mathcal{E}}, \sim_{\bar{\mathcal{C}}}, \sim_{\bar{\mathcal{E}}})$  be the corresponding natural quotient graph. See Figure 4. Any admissible  $g \in \mathcal{F}_{\bar{G}}^{\bar{P}}$  where  $\bar{P} = \mathbf{R}^3$  has the form

$$g(y) = (g_1(y_1), g_1(y_3), g_c(y_c, \overline{y_1, y_3})).$$

Moreover, any  $g_c(y_c, \overline{y_1, y_3})$  is a restriction of  $f_c(x_c, \overline{x_1, x_2, x_3, x_4})$  to the space

$$\Delta_1 = \{(y_1, y_1, y_3, y_3, y_c)\}$$

so  $\hat{\phi}$  is surjective.

(b) We consider now the same graph  $G$  but a different balanced equivalence relation  $\bowtie$  on  $\mathcal{C}$ . This time the  $\bowtie$ -equivalence classes are

$$\{1\}, \{2, 3, 4\}, \{c\}.$$

See Figure 5 for the natural quotient graph  $\bar{G}$ . As before,  $\bar{P} = \mathbf{R}^3$ . Any admissible  $h \in \mathcal{F}_{\bar{G}}^{\bar{P}}$  has the form

$$h(y) = (h_1(y_1), h_1(y_2), h_c(y_c, y_1, y_2)).$$

We can find  $h_c(y_c, y_1, y_2)$  that is not a restriction of  $f_c(x_c, \overline{x_1, x_2, x_3, x_4})$  to the space

$$\Delta_2 = \{(y_1, y_2, y_2, y_2, y_c)\}.$$

For example  $h_c(y_c, y_1, y_2) = y_1 + y_2$ . Therefore  $\hat{\phi}$  is not surjective in this case.

EXAMPLE 6.3. Consider the graph  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  of Figure 6 where the following hold.

- (i)  $\mathcal{C} = \{1, 2, 3, 4, c\}$ .
- (ii)  $\mathcal{E} = \{(1, 1), (2, 2), (3, 3), (4, 4), (c, c), (1, c), (2, c), (3, c), (4, c)\}$ .
- (iii)  $\sim_C$ -equivalence class:  $\{1, 2, 3, 4, c\}$ .
- (iv)  $\sim_E$ -equivalence classes:  $\{(1, 1), (2, 2), (3, 3), (4, 4), (c, c)\}, \{(1, c), (3, c)\}, \{(2, c), (4, c)\}$ .

Suppose that  $P = \mathbf{R}^5$ . Any admissible vector field  $f \in \mathcal{F}_G^P$  has the form

$$f(x) = (f_1(x_1), f_1(x_2), f_1(x_3), f_1(x_4), f_c(x_c, \overline{x_1, x_3}, \overline{x_2, x_4})).$$

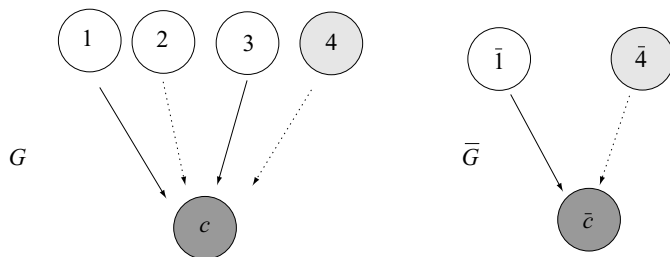


FIGURE 6. A coupled cell graph  $G$  and the corresponding natural quotient graph  $\bar{G}$  given by the equivalence relation  $\bowtie$  with classes  $\{1, 2, 3\}$ ,  $\{4\}$  and  $\{c\}$ .

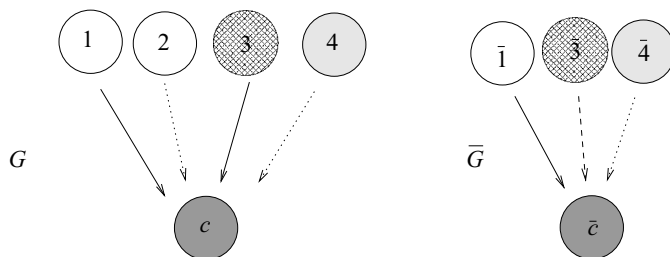


FIGURE 7. A coupled cell graph  $G$  and the corresponding natural quotient graph  $\bar{G}$  given by the equivalence relation  $\bowtie$  with classes  $\{1, 2\}$ ,  $\{3\}$ ,  $\{4\}$  and  $\{c\}$ .

(a) Consider the balanced equivalence relation  $\bowtie$  on  $\mathcal{C}$  with classes

$$\{1, 2, 3\}, \{4\}, \{c\}$$

and let  $\bar{G} = (\bar{\mathcal{C}}, \bar{\mathcal{E}}, \sim_{\bar{\mathcal{C}}}, \sim_{\bar{E}})$  be the corresponding natural quotient graph. Recall Figure 6. Any admissible  $g \in \mathcal{F}_{\bar{G}}^{\bar{P}}$  where  $\bar{P} = \mathbf{R}^3$  has the form

$$g(y) = (g_1(y_1), g_1(y_4), g_c(y_c, y_1, y_4)).$$

Moreover, any  $g_c(y_c, y_1, y_4)$  is a restriction of  $f_c(x_c, \overline{x_1, x_3}, \overline{x_2, x_4})$  to the space

$$\Delta_3 = \{(y_1, y_1, y_1, y_4, y_c)\}.$$

In this example,  $\hat{\phi}$  is surjective.

(b) We consider now the same graph  $G$  but a different balanced equivalence relation  $\bowtie$  on  $\mathcal{C}$ :

$$\{1, 2\}, \{3\}, \{4\}, \{c\}.$$

See Figure 7 for the natural quotient graph  $\bar{G}$ . Now  $\bar{P} = \mathbf{R}^4$ . Any admissible  $h \in \mathcal{F}_{\bar{G}}^{\bar{P}}$  has the form

$$h(y) = (h_1(y_1), h_1(y_3), h_1(y_4), h_c(y_c, y_1, y_3, y_4)).$$

Not every  $h_c(y_c, y_1, y_3, y_4)$  is a restriction of  $f_c(x_c, \overline{x_1, x_3}, \overline{x_2, x_4})$  to the space

$$\Delta_4 = \{(y_1, y_1, y_3, y_4, y_c)\}.$$

For example  $h_c(y_c, y_1, y_3, y_4) = y_1$  is not a restriction of this type, so  $\hat{\phi}$  is not surjective in this case.

7. Surjectivity of  $\hat{\phi}$

We now come to the main result of this paper. We give necessary and sufficient conditions for the map  $\hat{\phi}$  to be surjective. As explained earlier, we restrict attention to the natural quotient since otherwise  $\hat{\phi}$  cannot be surjective. The idea is as follows. We derive necessary conditions for the surjectivity of  $\hat{\phi}$  by considering vector fields with linear components. By applying invariant theory for  $\mathcal{B}_{\overline{C}}$ -equivariant maps, we prove that these conditions are also sufficient. We first carry out the proof for polynomial vector fields, and then extend it to the smooth case by standard methods.

Consider a coupled cell graph  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  and a balanced equivalence relation  $\bowtie$  on  $\mathcal{C}$ . Make a choice of phase space  $P$  (and so of  $\overline{P}$ ). Let  $\phi$  be the natural quotient map, and let  $\hat{\phi}$  be the corresponding map defined in Theorem 6.1. Recall that

$$\Delta_{\bowtie} = \{x \in P : x_c = x_d \text{ whenever } c \bowtie d, \forall c, d \in \mathcal{C}\}.$$

Take any  $c \in \mathcal{Q}$ , where  $\mathcal{Q}$  is a component of  $\mathcal{B}_G$ . Consider

$$I(c) = \{i \in \mathcal{C} : (i, c) \in \mathcal{E}\}$$

with a partition into subsets that lie in distinct  $\bowtie$ -equivalence classes

$$I(c) = \mathcal{O}_1 \dot{\cup} \dots \dot{\cup} \mathcal{O}_{\overline{n}(c)}. \tag{7.1}$$

Thus if  $a \in \mathcal{O}_i$  and  $b \in \mathcal{O}_j$  where  $i \neq j$ , then  $\overline{a} \neq \overline{b}$ .

DEFINITION 7.1. The sets  $\mathcal{O}_i$  and  $\mathcal{O}_j$  are *c-identical* or *B(c, c)-isomorphic* if there is  $\gamma \in B(c, c)$  such that

$$\gamma \mathcal{O}_i = \mathcal{O}_j.$$

If no  $\gamma$  exists that satisfies those conditions, then  $\mathcal{O}_i, \mathcal{O}_j$  are said to be *c-distinct*.

REMARK 7.2. In the notation of Subsection 5.3

$$\mathcal{O}_i = \Omega_c(\overline{a})$$

for any  $a \in \mathcal{O}_i$ . Let  $a \in \mathcal{O}_i$  and  $b \in \mathcal{O}_j$  where  $i \neq j$ . Then  $\mathcal{O}_i, \mathcal{O}_j$  are *c-identical* if and only if  $(\overline{a}, \overline{c}) \sim_{\overline{E}} (\overline{b}, \overline{c})$  (recall the definition of  $\sim_{\overline{E}}$  in (5.1)).

Consider the partition of the set  $\{1, \dots, \overline{n}(c)\}$  into subsets where each contains the indices  $i, j$  such that  $\mathcal{O}_i$  and  $\mathcal{O}_j$  are *c-identical*. If we denote by  $i$  the  $\bowtie$ -equivalence class of  $\mathcal{O}_i$  then we can write

$$I(\overline{c}) = \{1, \dots, \overline{n}(c)\} = \overline{K}_1 \dot{\cup} \dots \dot{\cup} \overline{K}_{\overline{r}(c)},$$

where  $\overline{K}_1, \dots, \overline{K}_{\overline{r}(c)}$  are the  $\equiv_{\overline{c}}$ -equivalence classes (on  $I(\overline{c})$ ), that is, the  $\overline{B}(\overline{c}, \overline{c})$ -orbits.

Let

$$B(c, c) = \mathbf{S}_{K_1} \times \dots \times \mathbf{S}_{K_{r(c)}},$$

where  $K_1 = \{c\}, K_2, \dots, K_{r(c)}$  are the  $\equiv_c$ -equivalence classes (on  $I(c)$ ). Recall (3.2).

We use the notation  $\mathbf{R}[z_1, \dots, z_m]$  for the polynomial ring in indeterminates  $z_1, \dots, z_m$  over  $\mathbf{R}$ , and  $\mathbf{R}\{z_1, \dots, z_m\}$  for the real vector space spanned by

$z_1, \dots, z_m$ . Thus let

$$\bar{V} = \mathbf{R}[Y_1, \dots, Y_{\bar{n}(c)}]$$

be the real vector space of polynomials in the indeterminates  $Y_1, \dots, Y_{\bar{n}(c)}$ , and let

$$V = \mathbf{R}[X_1, \dots, X_{n(c)}]$$

be the real vector space of polynomials in the indeterminates  $X_1, \dots, X_{n(c)}$ , where  $n(c)$  denotes the cardinality of  $I(c)$ .

Consider the subspace  $\bar{S}$  of  $\bar{V}$  defined by

$$\bar{S} = \mathbf{R} \left\{ \sum_{i \in \bar{K}_1} Y_i, \dots, \sum_{i \in \bar{K}_{\bar{r}(c)}} Y_i \right\}.$$

Thus  $\bar{S}$  contains the linear polynomials of  $\bar{V}$  that are  $\bar{B}(\bar{c}, \bar{c})$ -invariant. Let  $S$  be the subspace of  $V$  defined by

$$S = \mathbf{R} \left\{ \sum_{i \in K_1} X_i, \dots, \sum_{i \in K_{r(c)}} X_i \right\}.$$

That is,  $S$  is formed by the linear  $B(c, c)$ -invariants. Define

$$p_j(X) = \sum_{i \in K_j} X_i \equiv p_j(X_{K_j})$$

so that

$$S = \mathbf{R} \{p_1(X), \dots, p_{r(c)}(X)\}.$$

Consider

$$\bar{S}' = \mathbf{R} \{p_1(X'), \dots, p_{r(c)}(X')\}$$

where  $X'$  is defined in the following way. Given  $j = 1, \dots, \bar{n}(c)$ , then set

$$X'_i = Y_j \quad \forall i \in \mathcal{O}_j.$$

Informally, we can think of  $\bar{S}'$  as consisting of the elements of  $S$ , restricted to the subspace  $\Delta_{\bowtie}$ .

REMARK 7.3. By Theorem 6.1,  $\bar{S}'$  is clearly a subspace of  $\bar{S}$  and  $\dim(\bar{S}') \leq \min\{r(c), \bar{r}(c)\}$ . However,  $\bar{S}$  has dimension  $\bar{r}(c)$  where  $\bar{r}(c)$  is the number of  $\equiv_{\bar{c}}$ -equivalence classes in  $I(\bar{c})$ .

EXAMPLE 7.4. Let  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  where the following hold.

- (i)  $\mathcal{C} = \{1, 2, 3, 4, c\}$ .
- (ii)  $\mathcal{E} = \{(1, 1), (2, 2), (3, 3), (4, 4), (c, c), (1, c), (2, c), (3, c), (4, c)\}$ .
- (iii)  $\sim_C$ -equivalence class:  $\{1, 2, 3, 4, c\}$ .
- (iv)  $\sim_E$ -equivalence classes:  $\{(1, 1), (2, 2), (3, 3), (4, 4), (c, c)\}, \{(1, c)\}, \{(2, c), (3, c), (4, c)\}$ .

Consider the (balanced) equivalence relation  $\bowtie$  on  $\mathcal{C}$  with classes

$$\mathcal{O}_1 = \{1, 2\}, \quad \mathcal{O}_3 = \{3\}, \quad \mathcal{O}_4 = \{4\}, \quad \mathcal{O}_c = \{c\}$$

and let  $\bar{G} = (\bar{\mathcal{C}}, \bar{\mathcal{E}}, \sim_{\bar{C}}, \sim_{\bar{E}})$  be the corresponding natural quotient graph of  $G$  by  $\bowtie$ . See Figure 8.



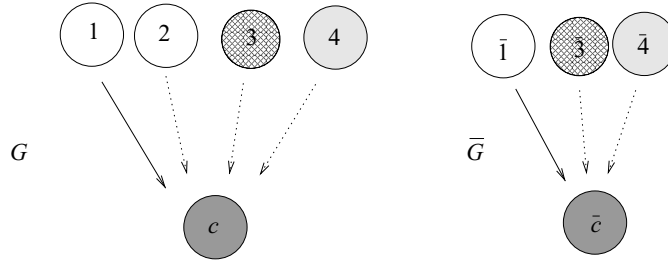


FIGURE 8. A coupled cell graph  $G$  and the corresponding natural quotient graph  $\bar{G}$  given by the equivalence relation  $\bowtie$  with classes  $\{1, 2\}$ ,  $\{3\}$ ,  $\{4\}$  and  $\{c\}$ .

Consider

$$V = \mathbf{R}[X_1, X_2, X_3, X_4, X_c], \quad \bar{V} = \mathbf{R}[Y_1, Y_3, Y_4, Y_c].$$

Since

$$I(c) = \mathcal{O}_1 \dot{\cup} \mathcal{O}_3 \dot{\cup} \mathcal{O}_4 \dot{\cup} \mathcal{O}_c$$

and  $\mathcal{O}_3, \mathcal{O}_4$  are  $c$ -identical, then

$$\bar{S} = \mathbf{R}\{Y_1, Y_3 + Y_4, Y_c\}$$

(and  $\bar{S} \subseteq \bar{V}$  has dimension 3). Also  $K_1 = \{1\}$ ,  $K_2 = \{2, 3, 4\}$ ,  $K_3 = \{c\}$  are the  $\equiv_c$ -equivalence classes:

$$I(c) = K_1 \dot{\cup} K_2 \dot{\cup} K_3, \quad B(c, c) = \mathbf{S}_{K_1} \times \mathbf{S}_{K_2} \times \mathbf{S}_{K_3}.$$

Thus

$$p_1(X) = X_1, \quad p_2(X) = X_2 + X_3 + X_4, \quad p_3(X) = X_c.$$

Recall that  $p_j(X) = \sum_{i \in K_j} X_i$ . Let

$$X' = (Y_1, Y_1, Y_3, Y_4, Y_c).$$

Then

$$\begin{aligned} \bar{S}' &= \mathbf{R}\{p_1(X'), p_2(X'), p_3(X')\} \\ &= \mathbf{R}\{Y_1, Y_1 + Y_3 + Y_4, Y_c\} \end{aligned}$$

and  $\bar{S}' = \bar{S}$ . We show below in Theorem 7.8 that the map  $\hat{\phi}$  is surjective for any choice of  $P$ .

Let  $d \in \mathcal{Q}$ , so that  $B(c, d) \neq \emptyset$ . Consider the partition of  $I(d)$  into subsets that lie in distinct  $\bowtie$ -equivalence classes

$$I(d) = \mathcal{O}'_1 \dot{\cup} \dots \dot{\cup} \mathcal{O}'_{\bar{n}(d)}.$$

DEFINITION 7.5. An input isomorphism  $\gamma \in B(c, d)$  is  $\bowtie$ -compatible if

$$i \bowtie j \iff \gamma(i) \bowtie \gamma(j)$$

for all  $i, j \in I(c)$ .

EXAMPLE 7.6. If  $\bowtie$  is balanced, then, by definition, whenever  $c \bowtie d$ , there exists a  $\bowtie$ -compatible  $\gamma \in B(c, d)$ .

REMARK 7.7. If there is a  $\bowtie$ -compatible  $\gamma \in B(c, d)$ , then  $\bar{n}(d) = \bar{n}(c)$ , and  $\mathcal{O}_i, \mathcal{O}_j$  are  $c$ -identical if and only if  $\gamma(\mathcal{O}_i), \gamma(\mathcal{O}_j)$  are  $d$ -identical. If  $\gamma$  is  $\bowtie$ -compatible, then it induces a map  $\bar{\gamma} \in \bar{B}(\bar{c}, \bar{d})$  defined by  $\bar{\gamma}(\bar{i}) = \overline{\gamma(i)}$  (see Definition 8.3); furthermore, any element of  $\bar{B}(\bar{c}, \bar{d})$  arises in this fashion (by Definition 5.3(c)). Thus  $\bar{B}(\bar{c}, \bar{d}) \neq \emptyset$  if and only if there is a  $\bowtie$ -compatible  $\gamma \in B(c, d)$ .

Our main result is the following.

THEOREM 7.8. Consider a coupled cell graph  $G = (\mathcal{C}, \mathcal{E}, \sim_C, \sim_E)$  and a balanced equivalence relation  $\bowtie$  on  $\mathcal{C}$ . Choose a total phase space  $P$  and form the corresponding space  $\bar{P}$ . Let  $\bar{G} = G / \bowtie$  be the natural quotient,  $\phi$  the natural quotient map, and let  $\hat{\phi}$  be the corresponding map on admissible vector fields defined in Theorem 6.1:

$$\begin{aligned} \hat{\phi}: \mathcal{F}_G^P &\longrightarrow \mathcal{F}_{\bar{G}}^{\bar{P}} \\ f &\longmapsto \bar{f}. \end{aligned}$$

Then  $\hat{\phi}$  is surjective if and only if the following hold.

- (1) For each connected component  $\mathcal{Q}$  of  $\mathcal{B}_G$ , for some (hence all)  $c \in \mathcal{Q}$ , we have  $\bar{\mathcal{S}}' = \bar{\mathcal{S}}$ .
- (2) The quotient map  $\phi$  defines a bijection between the connected components of  $\mathcal{B}_G$  and those of  $\mathcal{B}_{\bar{G}}$ .

Note that the same combinatorial conditions hold for any choice of total phase space  $P$ .

EXAMPLE 7.4 (continuation). In this example the connected components of  $\mathcal{B}_G$  are  $\mathcal{Q}_1 = \{1, 2, 3, 4\}$  and  $\mathcal{Q}_2 = \{c\}$  and those of  $\mathcal{B}_{\bar{G}}$  are  $\bar{\mathcal{Q}}_1 = \{\bar{1}, \bar{3}, \bar{4}\}$  and  $\bar{\mathcal{Q}}_2 = \{\bar{c}\}$ . Thus condition (2) of Theorem 7.8 is satisfied. We saw that for  $c \in \mathcal{Q}_2$  we have  $\bar{\mathcal{S}}' = \bar{\mathcal{S}}$  and so condition (1) of Theorem 7.8 is satisfied for  $\mathcal{Q}_2$ . Trivially, this condition is also satisfied for  $\mathcal{Q}_1$ . By Theorem 7.8, the map  $\hat{\phi}$  is surjective for any choice of  $P$ .

EXAMPLE 7.9. Recall Example 6.2. The connected components of  $\mathcal{B}_G$  are  $\mathcal{Q}_1 = \{1, 2, 3, 4\}$  and  $\mathcal{Q}_2 = \{c\}$ . Let

$$V = \mathbf{R}[X_1, X_2, X_3, X_4, X_c].$$

With the balanced equivalence relation considered in (a) (recall Figure 4)  $\mathcal{B}_{\bar{G}}$  also has two connected components:  $\bar{\mathcal{Q}}_1 = \{\bar{1}, \bar{3}\}$  and  $\bar{\mathcal{Q}}_2 = \{\bar{c}\}$ . Thus condition (2) of Theorem 7.8 is satisfied. Consider now

$$\bar{V} = \mathbf{R}[Y_1, Y_3, Y_c].$$

Denote by

$$\mathcal{O}_1 = \{1, 2\}, \quad \mathcal{O}_3 = \{3, 4\}, \quad \mathcal{O}_c = \{c\}$$

the  $\bowtie$ -equivalence classes. Since

$$I(c) = \mathcal{O}_1 \dot{\cup} \mathcal{O}_3 \dot{\cup} \mathcal{O}_c$$

and  $\mathcal{O}_1, \mathcal{O}_3$  are  $c$ -identical, then

$$\overline{B}(\overline{c}, \overline{c}) = \mathbf{S}_{\{1,3\}} \times \mathbf{S}_{\{c\}}$$

and

$$\overline{S} = \mathbf{R}\{Y_1 + Y_3, Y_c\}.$$

Thus  $\overline{S} \subseteq \overline{V}$  has dimension 2. Also  $K_1 = \{1, 2, 3, 4\}$  and  $K_2 = \{c\}$  are the  $\equiv_c$ -equivalence classes:

$$I(c) = K_1 \dot{\cup} K_2, \quad B(c, c) = \mathbf{S}_{K_1} \times \mathbf{S}_{K_2}.$$

Thus

$$p_1(X) = X_1 + X_2 + X_3 + X_4, \quad p_2(X) = X_c$$

and

$$S = \mathbf{R}\{p_1(X), p_2(X)\}.$$

Let

$$X' = (Y_1, Y_1, Y_3, Y_3, Y_c).$$

Then

$$\begin{aligned} \overline{S}' &= \mathbf{R}\{p_1(X'), p_2(X')\} \\ &= \mathbf{R}\{2(Y_1 + Y_3), Y_c\} \end{aligned}$$

and  $\overline{S}' = \overline{S}$ . Thus condition (1) of Theorem 7.8 is satisfied for  $\mathcal{Q}_2$ . Trivially this condition is also satisfied for  $\mathcal{Q}_1$ . Note that for  $i \in \mathcal{Q}_1$  we have  $I(i) = \{i\}$ . Thus by Theorem 7.8 the map  $\hat{\phi}$  is surjective for any choice of  $P$ .

For the balanced equivalence relation considered in (b) (recall Figure 5), again  $\mathcal{B}_{\overline{C}}$  has two connected components  $\overline{\mathcal{Q}}_1 = \{\overline{1}, \overline{2}\}$  and  $\overline{\mathcal{Q}}_2 = \{\overline{c}\}$ . Thus condition (2) of Theorem 7.8 is also satisfied. Consider now

$$\overline{V} = \mathbf{R}[Y_1, Y_2, Y_c]$$

and

$$\mathcal{O}_1 = \{1\}, \quad \mathcal{O}_2 = \{2, 3, 4\}, \quad \mathcal{O}_c = \{c\}$$

the  $\bowtie$ -equivalence classes. As

$$I(c) = \mathcal{O}_1 \dot{\cup} \mathcal{O}_2 \dot{\cup} \mathcal{O}_c$$

and  $\mathcal{O}_1, \mathcal{O}_2$  are  $c$ -distinct, then

$$\overline{S} = \mathbf{R}\{Y_1, Y_2, Y_c\}$$

(and  $\overline{S} = \overline{V}$  has dimension 3). As before  $K_1 = \{1, 2, 3, 4\}$ ,  $K_2 = \{c\}$  are the  $\equiv_c$ -equivalence classes:

$$I(c) = K_1 \dot{\cup} K_2, \quad B(c, c) = \mathbf{S}_{K_1} \times \mathbf{S}_{K_2}$$

and

$$S = \mathbf{R}\{X_1 + X_2 + X_3 + X_4, X_c\}.$$

Taking now

$$X' = (Y_1, Y_2, Y_2, Y_2, Y_c)$$

we get

$$\overline{S}' = \mathbf{R}\{Y_1 + 3Y_2, Y_c\}$$

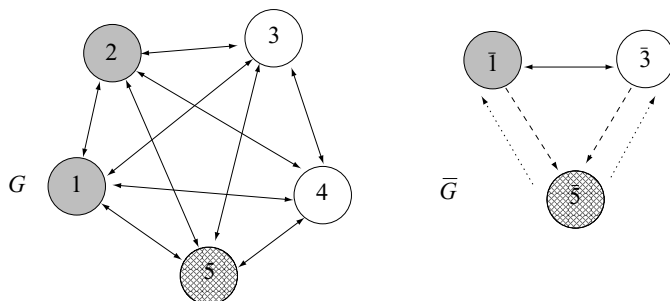


FIGURE 9. A coupled cell graph  $G$  with  $\mathbf{S}_5$ -symmetry and the corresponding natural quotient graph  $\bar{G}$  with  $\mathbf{Z}_2$ -symmetry given by the equivalence relation  $\bowtie$  with classes  $\{1, 2\}$ ,  $\{3, 4\}$  and  $\{5\}$ .

and  $\bar{S}' \neq \bar{S}$ . Thus condition (1) of Theorem 7.8 is not satisfied for  $\mathcal{Q}_2$  and so the map  $\hat{\phi}$  is not surjective (for any choice of  $P$ ).

EXAMPLE 7.10. Let  $G$  be a coupled cell graph consisting of five identical cells with all-to-all identical coupling. Say  $\mathcal{C} = \{1, 2, 3, 4, 5\}$ . Consider the balanced equivalence relation  $\bowtie$  on  $\mathcal{C}$  with classes

$$\{1, 2\}, \{3, 4\}, \{5\}$$

and let  $\bar{G} = (\bar{\mathcal{C}}, \bar{\mathcal{E}}, \sim_{\bar{\mathcal{C}}}, \sim_{\bar{\mathcal{E}}})$  be the corresponding natural quotient graph. See Figure 9.

In this example  $\mathcal{B}_G$  is connected since all cells in  $\mathcal{C}$  are input equivalent. However  $\mathcal{B}_{\bar{G}}$  is not connected. It has two connected components:  $\bar{\mathcal{Q}}_1 = \{\bar{1}, \bar{3}\}$  and  $\bar{\mathcal{Q}}_2 = \{\bar{5}\}$ . Thus condition (2) of Theorem 7.8 is not satisfied and the map  $\hat{\phi}$  is not surjective (for any choice of  $P$ ). We return to this example in Subsection 8.3.

The proof of Theorem 7.8 is accomplished in two steps. The main work goes into proving the result for polynomial vector fields. We then extend the theorem to smooth vector fields using the well-known result of Schwarz [15].

We begin by proving Theorem 7.8 for vector fields with polynomial components. Let  $\mathcal{P}_G^P$  and  $\mathcal{P}_{\bar{G}}^{\bar{P}}$  denote the classes of admissible polynomial vector fields for  $G$  and  $\bar{G}$ .

PROPOSITION 7.11. *The function*

$$\begin{aligned} \hat{\phi} : \mathcal{P}_G^P &\longrightarrow \mathcal{P}_{\bar{G}}^{\bar{P}} \\ f &\longmapsto \bar{f} \end{aligned}$$

is surjective if and only if conditions (1) and (2) of Theorem 7.8 are satisfied.

*Proof.* We start by proving that conditions (1) and (2) of Proposition 7.11 are necessary for  $\hat{\phi}$  to be surjective. Let  $f$  be any admissible polynomial vector field in  $\mathcal{P}_G^P$ . By Theorem 4.2, for any component  $\mathcal{Q}$  of  $\mathcal{B}_G$  and  $c \in \mathcal{Q}$ ,  $\mathcal{B}_G$ -equivariance of  $f$  on the components  $f_d : P_{I(d)} \longrightarrow P_d = P_c$  with  $d \in \mathcal{Q}$  is equivalent to the following.

- (a)  $B(c, c)$ -invariance of  $f_c : P_{I(c)} \longrightarrow P_c$ .
- (b)  $f_d(x_{I(d)}) = f_c(\beta^*(x_{I(d)}))$  for some  $\beta \in B(c, d)$ .

Suppose that  $c, d \in \mathcal{Q}$ , and there is no  $\bowtie$ -compatible  $\beta \in B(c, d)$ . Then  $\overline{B}(\overline{c}, \overline{d}) = \emptyset$ . Therefore,  $\mathcal{B}_{\overline{c}}$ -equivariance does not impose any relation between the  $\overline{f}_{\overline{c}}$  and  $\overline{f}_{\overline{d}}$  components. Thus  $\hat{\phi}$  cannot be surjective in this case.

Alternatively, there exists some  $\bowtie$ -compatible  $\beta \in B(c, d)$ . Then

$$\overline{f}_{\overline{d}}\left(y_{I(\overline{d})}\right) = \overline{f}_{\overline{c}}\left(\overline{\beta}^*\left(y_{I(\overline{d})}\right)\right)$$

for some  $\overline{\beta} \in \overline{B}(\overline{c}, \overline{d})$  induced by  $\beta$ . In this case  $\hat{\phi}$  is surjective if and only if

$$\begin{aligned} \text{any } \overline{B}(\overline{c}, \overline{c})\text{-invariant } \overline{f}_{\overline{c}}: \overline{P}_{I(\overline{c})} \longrightarrow \overline{P}_{\overline{c}} \text{ is a restriction to } \Delta_{\bowtie} \\ \text{of some } B(c, c)\text{-invariant } f_c: P_{I(c)} \longrightarrow P_c. \end{aligned} \tag{7.2}$$

Here

$$P_{I(c)} = \prod_{i \in I(c)} P_i, \quad \overline{P}_{I(\overline{c})} = \prod_{j \in I(\overline{c})} \overline{P}_j.$$

Moreover, (7.2) is valid if and only if the same condition is valid for each real component of  $f_{\overline{c}}$ . (Recall that the space  $P_{\overline{c}} = P_c$  can be any finite-dimensional real vector space.) That is, all the real-valued  $\overline{B}(\overline{c}, \overline{c})$ -invariants on  $\overline{P}_{I(\overline{c})}$  are restrictions to the space  $\Delta_{\bowtie}$  of real-valued  $B(c, c)$ -invariants on  $P_{I(c)}$ .

Using the notation after Remark 7.2, it follows that

$$\overline{B}(\overline{c}, \overline{c}) = \mathbf{S}_{\overline{K}_1} \times \dots \times \mathbf{S}_{\overline{K}_{\overline{r}(c)}}$$

and  $\overline{r}(c)$  is the number of  $\equiv_{\overline{c}}$ -equivalence classes in  $I(\overline{c})$ . If the space  $\overline{S}'$  has dimension lower than  $\overline{r}(c)$ , then trivially we can find linear  $\overline{B}(\overline{c}, \overline{c})$ -invariants that are not the restriction to  $\Delta_{\bowtie}$  of (linear)  $B(c, c)$ -invariants. Thus in this case, the map  $\hat{\phi}$  is not surjective.

We prove now that if the dimension of  $\overline{S}'$  equals  $\overline{r}(c)$ , then  $\hat{\phi}$  is surjective. Using Lemma 7.12 below, it is sufficient to prove that when the hypothesis is valid, any  $\mathbf{S}_{\overline{K}_i}$ -invariant (depending only on the  $y_j$  with  $j \in \overline{K}_i$ ) is the restriction to  $\Delta_{\bowtie}$  of a  $B(c, c)$ -invariant. Lemma 7.13 below then completes the proof.  $\square$

It remains to prove the two lemmas.

LEMMA 7.12. *Consider  $V_1^{d_1}, \dots, V_s^{d_s}$ , where each  $V_i$  is a finite-dimensional vector space, say with dimension  $k_i$ , and denote by  $x_i = (x_{i,1}, \dots, x_{i,d_i})$  coordinates on  $V_i^{d_i}$ . Thus each  $x_{i,j}$  is a vector with  $k_i$  components. Let*

$$\Gamma = \mathbf{S}_{d_1} \times \dots \times \mathbf{S}_{d_s}$$

and

$$V = V_1^{d_1} \times \dots \times V_s^{d_s}$$

with a  $\Gamma$ -action on  $V$  defined in the following way: if  $\sigma \in \mathbf{S}_{d_i}$ , then

$$\sigma \cdot x = (x_1, \dots, x_{i-1}, \sigma \cdot x_i, x_{i+1}, \dots, x_s),$$

where

$$\sigma \cdot x_i = (x_{i,\sigma(1)}, \dots, x_{i,\sigma(d_i)}).$$

Then any real  $\Gamma$ -invariant polynomial is a sum of polynomials of the form

$$q_1(x_1)q_2(x_2) \dots q_s(x_s),$$

where for  $j = 1, \dots, s$ , each  $q_j(x_j)$  is  $\mathbf{S}_{d_j}$ -invariant.

*Proof.* The idea of the proof is simple but the notation is complicated. Essentially, we use the fact that any invariant can be obtained as a linear combination of symmetrized monomials, so the proof reduces to computations with monomials.

In detail, recall that  $p: V \rightarrow \mathbf{R}$  is  $\Gamma$ -invariant if and only if

$$p(\sigma \cdot x) = p(x) \quad \forall \sigma \in \Gamma, x \in V.$$

This condition holds if and only if  $p: V \rightarrow \mathbf{R}$  is  $\mathbf{S}_{d_i}$ -invariant, where  $\mathbf{S}_{d_i}$  acts non-trivially only on  $V_i^{d_i}$ .

Denote by  $\mathbf{Z}_0^+$  the set of non-negative integers. Monomials in  $x_1$  have the form

$$x_{1,1}^{I_1} \dots x_{1,d_1}^{I_{d_1}}$$

where  $I_1, \dots, I_{d_1} \in (\mathbf{Z}_0^+)^{k_1}$ , and each  $x_{1,j}^{I_j}$  is a monomial in the  $k_1$  components of  $x_{1,j}$ .

Let  $p: V \rightarrow \mathbf{R}$  be a  $\Gamma$ -invariant polynomial, and write it as a linear combination of monomials in  $x_1$  with coefficients in  $\mathbf{R}[x_2, \dots, x_s]$ . Suppose that  $p(x)$  contains a term that is a scalar multiple of

$$x_{1,1}^{I_1} \dots x_{1,d_1}^{I_{d_1}} q(x_2, \dots, x_s).$$

Since  $p$  is  $\mathbf{S}_{d_1}$ -invariant and  $\mathbf{S}_{d_1}$  acts trivially on  $x_2, \dots, x_s$ , then  $p(x)$  must also contain

$$x_{1,\sigma(1)}^{I_1} \dots x_{1,\sigma(d_1)}^{I_{d_1}} q(x_2, \dots, x_s)$$

for all  $\sigma \in \mathbf{S}_{d_1}$ . It follows that  $p(x)$  contains a scalar multiple of

$$\left( \sum_{\sigma \in \mathbf{S}_{d_1}} x_{1,\sigma(1)}^{I_1} \dots x_{1,\sigma(d_1)}^{I_{d_1}} \right) q(x_2, \dots, x_s) = q_1(x_1) \cdot q(x_2, \dots, x_s)$$

where  $q_1(x_1) = \sum_{\sigma \in \mathbf{S}_{d_1}} x_{1,\sigma(1)}^{I_1} \dots x_{1,\sigma(d_1)}^{I_{d_1}}$ . Now we repeat the same argument for  $q(x_2, \dots, x_s)$  inductively. □

Suppose that  $\overline{K}_1 = \{1, \dots, t\}$ . Thus  $\mathbf{S}_{\overline{K}_1} = \mathbf{S}_t$ . Denote by  $o_i$  the cardinality of  $\mathcal{O}_i$  for any  $i \in \{1, \dots, \overline{n}(c)\}$ . Observe that  $\mathcal{O}_1, \dots, \mathcal{O}_t$  all have the same cardinality since they are  $c$ -identical. Moreover, we may (if necessary) reorder the cells  $x_i$  so that  $\mathcal{O}_1 = \{1, \dots, o_1\}$ ,  $\mathcal{O}_2 = \{o_1 + 1, \dots, 2o_1\}, \dots$

LEMMA 7.13. *Suppose that  $\overline{S}'$  has dimension  $\overline{r}(c)$ . Let  $P_k = V$  for all  $k \in \mathcal{O}_1 \cup \dots \cup \mathcal{O}_t$ , where  $V$  is any finite-dimensional real vector space. Then any real  $\mathbf{S}_t$ -invariant polynomial  $p: V^t \rightarrow \mathbf{R}$  is a restriction to the space*

$$\Delta = \left\{ \left( \underbrace{y_1, \dots, y_1}_{o_1}, \dots, \underbrace{y_t, \dots, y_t}_{o_1}, \underbrace{y_{t+1}, \dots, y_{t+1}}_{o_{t+1}}, \dots, \underbrace{y_{\overline{n}(c)}, \dots, y_{\overline{n}(c)}}_{o_{\overline{n}(c)}} \right) : y_1, \dots, y_t \in V \right\}$$

(where  $y_{t+1}, \dots, y_{\overline{n}(c)}$  are fixed constants) of a real  $B(c, c)$ -invariant polynomial defined on

$$\underbrace{V^{o_1} \times \dots \times V^{o_1}}_t \times P_{t+1}^{o_{t+1}} \times \dots \times P_{\overline{n}(c)}^{o_{\overline{n}(c)}}.$$

*Proof.* Observe that

$$\Delta = \Delta_{\bowtie} \cap P_{I(c)}.$$

Suppose that  $V$  has dimension  $d$ . Choose coordinates  $(y_1, \dots, y_t)$  on  $V^t$ , where  $y_i = (y_{i,1}, \dots, y_{i,d})$ . Thus, if  $\sigma \in \mathbf{S}_t$ , then

$$\sigma \cdot (y_1, \dots, y_t) = (y_{\sigma(1)}, \dots, y_{\sigma(t)})$$

where

$$y_{\sigma(i)} = (y_{\sigma(i),1}, \dots, y_{\sigma(i),d}).$$

A real polynomial  $\mathbf{S}_t$ -invariant on  $V^t$  is a linear combination of  $\mathbf{S}_t$ -invariants of the form

$$\sum_{\sigma \in \mathbf{S}_t} y_{\sigma(1)}^{I_1} \cdots y_{\sigma(t)}^{I_t} \tag{7.3}$$

where  $I_i \in (\mathbf{Z}_0^+)^d$ .

We must prove that

any polynomial of the form (7.3) is the restriction to  $\Delta$  of a  $B(c, c)$ -invariant. (7.4)

The proof is performed by induction, and makes use of the following definition.

**DEFINITION 7.14.** A polynomial (7.3) is of *type*  $m$ , where  $1 \leq m \leq t$ , if only  $m$  sets of indices, without loss of generality,  $I_1, \dots, I_m$ , are non-zero. That is,  $I_{m+1} = \dots = I_t = (0, \dots, 0)$ , and  $I_j \neq (0, \dots, 0)$  for  $j = 1, \dots, m$ .

We prove (7.4) by induction on the type  $m$ . If  $m = 1$ , then given any  $I_1 \in (\mathbf{Z}_0^+)^d$ , an expression (7.3) of type 1 has the form

$$p_{I_1}(y) = \sum_{\sigma \in \mathbf{S}_t} y_{\sigma(1)}^{I_1} = y_1^{I_1} + \dots + y_t^{I_1}.$$

Since  $\overline{S}'$  has dimension  $\overline{r}(c)$ , which is the dimension of  $\overline{S}$ , the subspaces  $\overline{S}$  and  $\overline{S}'$  are equal (recall Remark 7.3). Therefore there exist real coefficients  $\alpha_1, \alpha_2, \dots$ , such that

$$Y_1 + \dots + Y_t = \alpha_1 p_1(X') + \alpha_2 p_2(X') + \dots \tag{7.5}$$

since  $Y_1 + \dots + Y_t \in \overline{S}$ . We claim that the  $p_i(X')$  that appear in (7.5) can be chosen to depend only on  $Y_j$ , where  $j \sim_{\overline{C}} 1$ . For all  $i \in \{1, \dots, t\}$  we know that  $(1, \overline{c}) \sim_{\overline{E}} (i, \overline{c})$ , and so  $1 \sim_{\overline{C}} i$ . Also, all the cells in the same  $\equiv_c$ -equivalence class are  $\sim_C$ -equivalent. Thus if some  $p_i(X')$  in (7.5) depends on  $Y_l, Y_j$  such that  $l \in \{1, \dots, t\}$  and  $j \notin \{1, \dots, t\}$ , then  $j \sim_{\overline{C}} l$  since  $j = \overline{k}$  and  $l = \overline{k'}$  for some  $k, k' \in K_i$ , and so  $k \sim_C k'$ .

Set  $Y_j = y_j^{I_1}$  and  $X_j = x_j^{I_1}$  for all  $j$ . Thus,  $X'_j = X_j|_{\Delta}$ , so that  $p_j(X') = p_j(X)|_{\Delta}$ . Substituting all of this into equation (7.5) we get

$$p_{I_1}(y) = \sum_{\sigma \in \mathbf{S}_t} y_{\sigma(1)}^{I_1} = \sum_{i=1}^t Y_i = \alpha_1 p_1(X)|_{\Delta} + \alpha_2 p_2(X)|_{\Delta} + \dots = q_{I_1}(x)|_{\Delta},$$

where

$$q_{I_1}(x) = \alpha_1 \left( \sum_{i \in K_1} x_i^{I_1} \right) + \alpha_2 \left( \sum_{i \in K_2} x_i^{I_1} \right) + \dots$$

is a  $B(c, c)$ -invariant.

We suppose that any polynomial of the form (7.3) of type less than or equal to  $m$  is the restriction to  $\Delta$  of a  $B(c, c)$ -invariant. We now prove that the same holds for polynomials of type  $m + 1$ . Consider

$$p_{I_1, \dots, I_{m+1}}(y) = \sum_{\sigma \in \mathbf{S}_t} y_{\sigma(1)}^{I_1} y_{\sigma(2)}^{I_2} \cdots y_{\sigma(m+1)}^{I_{m+1}}.$$

Take the  $\mathbf{S}_t$ -invariant polynomial

$$p(y) = p_{I_1}(y) \cdots p_{I_{m+1}}(y)$$

where

$$p_{I_i}(y) = \sum_{\sigma \in \mathbf{S}_t} y_{\sigma(1)}^{I_i}.$$

By the base case,  $p_{I_j}(y) = q_{I_j}(x)|_{\Delta}$  for all  $j$ . Thus

$$p(y) = [q_{I_1}(x) \cdots q_{I_{m+1}}(x)]|_{\Delta},$$

where

$$q_{I_j}(x) = \alpha_1 \left( \sum_{i \in K_1} x_i^{I_j} \right) + \alpha_2 \left( \sum_{i \in K_2} x_i^{I_j} \right) + \dots$$

is a  $B(c, c)$ -invariant. Moreover

$$p(y) = p_{I_1, \dots, I_{m+1}}(y) + \sum_i \beta_i r_i(y),$$

where each  $\beta_i \in \mathbf{R}$  and each  $r_i(y)$  is an  $\mathbf{S}_t$ -invariant of the form (7.3) and of type less than or equal to  $m$ . By hypothesis

$$r_i(y) = s_i(x)|_{\Delta}$$

for some  $B(c, c)$ -invariant  $s_i(x)$ . Thus

$$p_{I_1, \dots, I_{m+1}}(y) = \left[ q_{I_1}(x) \cdots q_{I_{m+1}}(x) - \sum_i \beta_i s_i(x) \right] \Big|_{\Delta}. \quad \square$$

We now use Proposition 7.11 in the corresponding result for smooth vector fields.

*Proof of Theorem 7.8.* As shown in Proposition 7.11, if either of the two conditions fails, then  $\hat{\phi}$  is not surjective when considered as a map of polynomial vector fields. It is clear that  $\hat{\phi}$  preserves jets (Taylor series) of smooth mappings, so the theorem of Borel (Bröcker and Lander [1, Theorem 4.9]) implies that  $\hat{\phi}$  is not surjective when considered as a map of smooth vector fields.

Conversely, suppose that the two conditions are valid, so that  $\hat{\phi}$  is surjective on equivariant polynomial vector fields. We claim that it is also surjective on equivariant smooth vector fields. This is a consequence of Theorem 4.2, which implies that every smooth equivariant vector field  $f$  is determined uniquely by its components  $f_c$  where  $c$  runs through a set of representatives  $\mathcal{R}$  for the connected components (that is, the  $\sim_I$ -classes) of the groupoid  $\mathcal{B}_G$ . The only constraints on  $f_c$  are that it depends only on  $x_{I(c)}$  and is invariant under the vertex group  $B(c, c)$ . Thus every smooth equivariant vector field  $f$  is determined uniquely by a finite set of  $B(c, c)$ -invariant functions, for  $c \in \mathcal{R}$ . Moreover, if  $d \sim_I c$  then  $f_d$  is related to  $f_c$  by a pullback map  $\beta^*$  for  $\beta \in B(c, d)$ . Pullbacks permute variables, hence preserve smoothness (and also map polynomials to polynomials).



Schwarz [15] (see also Mather [13] and Luna [10]) proves that in general for any compact Lie group  $\Gamma$  with an orthogonal action on  $\mathbf{R}^n$ , if the algebra of  $\Gamma$ -invariant polynomials is generated by  $\rho_1, \dots, \rho_k$  (and by Hilbert’s basis theorem such a basis always exists), then any  $\Gamma$ -invariant  $C^\infty$ -function of  $n$  variables is a  $C^\infty$ -function of the generators  $\rho_1, \dots, \rho_k$ . Thus  $\hat{\phi}$  induces a surjective map on these polynomial generators. If  $d \sim_I c \in \mathcal{R}$  then we can apply a pullback map to determine the component  $f_d$  from  $f_c$ . Since  $\hat{\phi}$  induces a surjective map on invariant polynomials, it must also induce a surjective map on smooth equivariant vector fields.  $\square$

### 8. Relation to quotient groupoids

Given a graph  $G$  and a balanced equivalence relation  $\bowtie$  on the nodes of  $G$ , Subsection 5.3 describes a method for constructing the natural quotient graph  $\overline{G} = G / \bowtie$  and the associated quotient map  $\phi$ . In [17] it is proved that  $\phi$  is a quotient map between the graphs. We now prove that  $\phi$  naturally induces a groupoid map  $\phi' : \mathcal{T}_G^{\bowtie} \rightarrow \mathcal{B}_{\overline{G}}$ . Here  $\mathcal{T}_G^{\bowtie}$  is the subgroupoid of  $\mathcal{B}_G$  comprising the  $\bowtie$ -compatible input isomorphisms, and  $\mathcal{B}_{\overline{G}}$  is the symmetry groupoid of  $\overline{G}$ .

Moreover, we prove that the map  $\phi'$  is a groupoid quotient map, and deduce that  $\mathcal{T}_G^{\bowtie} / \ker(\phi') \cong \mathcal{B}_{\overline{G}}$ . Indeed, we show that the groupoid situation is analogous to the ‘normalizer quotient’ property in the group-symmetric case, discussed in the introduction.

#### 8.1. Background

We start by recalling from Higgins [9] the definitions of a quotient groupoid and a groupoid quotient map.

A subgroupoid  $\mathcal{N} = \bigcup N(a, b)$  of a groupoid  $\mathcal{G} = \bigcup G(a, b)$  is *normal* if the following hold.

(a)  $\mathcal{N}$  contains all the identity elements of  $\mathcal{G}$ , so in particular  $\mathcal{G}$  and  $\mathcal{N}$  have the same objects.

(b) If  $\sigma \in N(a, a)$  and  $\alpha \in G(b, a)$ , then  $\alpha^{-1}\sigma\alpha \in N(b, b)$ .

Let  $\mathcal{N} = \bigcup N(a, b)$  be a normal subgroupoid of  $\mathcal{G}$ . Define an equivalence relation  $\sim_{\mathcal{N}}$  on the objects of  $\mathcal{G}$ :

$$a \sim_{\mathcal{N}} b \iff N(a, b) \neq \emptyset \quad \text{for } a, b \in \mathcal{O},$$

where  $\mathcal{O}$  is the set of objects of  $\mathcal{G}$  (and  $\mathcal{N}$ ). Denote by  $\overline{a}$  the equivalence class of  $a \in \mathcal{O}$ , and let  $\overline{\mathcal{O}}$  be the set of classes. Define an equivalence relation (also denoted  $\sim_{\mathcal{N}}$ ) on the maps of  $\mathcal{G}$ :

$$\alpha, \beta \in \mathcal{G}, \quad \alpha \sim_{\mathcal{N}} \beta \iff \exists \mu, \nu \in \mathcal{N}, \quad \alpha = \mu\beta\nu.$$

The equivalence classes are the cosets  $\mathcal{N}\alpha\mathcal{N}$ , which we denote by  $\overline{\alpha}$ . The product  $\overline{\alpha}\overline{\beta}$  is defined if and only if there exist  $\alpha' \in \overline{\alpha}$  and  $\beta' \in \overline{\beta}$  such that  $\alpha'\beta'$  is defined; in this case

$$\overline{\alpha}\overline{\beta} = \overline{\alpha\beta}. \tag{8.1}$$

The *quotient groupoid*  $\mathcal{G}/\mathcal{N}$  is the groupoid whose objects are  $\overline{\mathcal{O}}$ , whose maps are the  $\overline{\alpha}$ , and which has product operation (8.1).

If  $\mathcal{G}$  and  $\overline{\mathcal{G}}$  are categories, then a *functor*  $\phi: \mathcal{G} \rightarrow \overline{\mathcal{G}}$  assigns to each object  $a$  of  $\mathcal{G}$  an object  $\phi(a)$  of  $\overline{\mathcal{G}}$ , and to each  $\mathcal{G}$ -morphism  $\alpha \in G(a, b)$  a  $\overline{\mathcal{G}}$ -morphism  $\phi(\alpha)$  of  $\overline{G}(\phi(a), \phi(b))$  in such a manner that the following hold.

- (a)  $\phi(\epsilon_a) = \epsilon_{\phi(a)}$  for each  $a$ .
- (b)  $\phi(\alpha\beta) = \phi(\alpha)\phi(\beta)$  whenever  $\alpha\beta$  is defined.

If  $\mathcal{G}$  and  $\overline{\mathcal{G}}$  are groupoids, then a *groupoid map*  $\phi: \mathcal{G} \rightarrow \overline{\mathcal{G}}$  is a functor from  $\mathcal{G}$  to  $\overline{\mathcal{G}}$ . Observe that  $\phi$  then preserves inverses. The *kernel* of  $\phi$  is defined by

$$\ker(\phi) = \{\alpha \in \mathcal{G} : \phi(\alpha) = \epsilon_a \text{ for some object } a \in \overline{\mathcal{G}}\}$$

and it is a normal subgroupoid of  $\mathcal{G}$ .

A groupoid map  $\phi: \mathcal{G} \rightarrow \overline{\mathcal{G}}$  with kernel  $\mathcal{N}$  is a *quotient map* if it induces a unique groupoid map  $\phi^*: \mathcal{G}/\mathcal{N} \rightarrow \overline{\mathcal{G}}$  which is an isomorphism [9, Proposition 24, p. 87].

A groupoid map  $\phi: \mathcal{G} \rightarrow \overline{\mathcal{G}}$  is

- (a) *vertex-surjective* if  $\phi: \mathcal{O} \rightarrow \overline{\mathcal{O}}$  is a surjection;
- (b) *piecewise-surjective* if  $\phi: G(a, b) \rightarrow \overline{G}(\phi(a), \phi(b))$  is surjective for each pair  $(a, b)$  of objects of  $\mathcal{G}$ .

**THEOREM 8.1.** *A groupoid map  $\phi: \mathcal{G} \rightarrow \overline{\mathcal{G}}$  is a quotient map if and only if  $\phi$  is vertex-surjective and piecewise surjective.*

*Proof.* See [9, Proposition 25, p. 88]. □

### 8.2. Quotient groupoid map

Define

$$\mathcal{T}_G^\bowtie = \bigcup T(c, d),$$

where

$$T(c, d) = \{(\beta, c, d) \in B(c, d) : \beta \text{ is } \bowtie\text{-compatible}\}.$$

**LEMMA 8.2.**  *$\mathcal{T}_G^\bowtie$  is a subgroupoid of  $\mathcal{B}_G$ .*

*Proof.* Recall that

$$T(c, d) = \{(\beta, c, d) \in B(c, d) : i \bowtie j \iff \beta(i) \bowtie \beta(j), \forall i, j \in I(c)\}$$

(Definition 7.5). Thus if  $(\beta_1, a, b) \in B(a, b)$ ,  $(\beta_2, b, c) \in B(b, c)$  and  $\beta_1, \beta_2$  are both  $\bowtie$ -compatible, then  $(\beta_2\beta_1, a, c) \in B(a, c)$  and  $\beta_2\beta_1$  is  $\bowtie$ -compatible. Also  $(\beta_1^{-1}, b, a) \in B(b, a)$  and  $\beta_1^{-1}$  is  $\bowtie$ -compatible. □

**DEFINITION 8.3.** We define  $\phi': \mathcal{T}_G^\bowtie \rightarrow \mathcal{B}_{\overline{\mathcal{G}}}$  in the following way.

(i) *Objects:*  $\phi': \mathcal{C} \rightarrow \overline{\mathcal{C}}$  is such that  $\phi'(c) = \phi(c) = \overline{c}$ . By the definition of  $\overline{\mathcal{C}}$  this map is vertex-surjective.

(ii) *Morphisms:* Given  $c, d \in \mathcal{C}$  (and  $T(c, d) \neq \emptyset$ ), then

$$\begin{aligned} \phi' : \quad & T(c, d) \longrightarrow \overline{B}(\overline{c}, \overline{d}) \\ & (\beta, c, d) \longmapsto (\beta', \overline{c}, \overline{d}), \end{aligned} \tag{8.2}$$

where

$$\beta'(\overline{i}) = \overline{\beta(i)}, \quad i \in I(c). \tag{8.3}$$

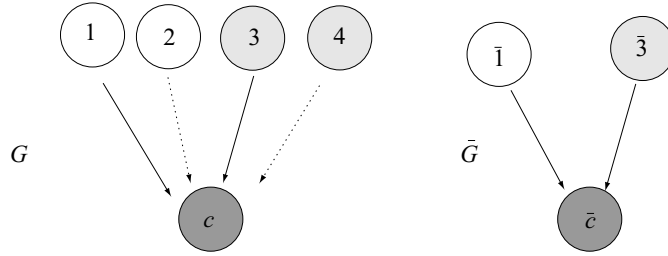


FIGURE 10. A coupled cell graph  $G$  and the corresponding natural quotient graph  $\bar{G}$  given by the equivalence relation  $\bowtie$  with classes  $\{1, 2\}$ ,  $\{3, 4\}$  and  $\{c\}$ .

Along with  $T_G^{\bowtie}$  we require the following definition.

DEFINITION 8.4. Let  $S_G^{\bowtie} = \dot{\bigcup} S(c, d)$  be the subgroupoid of  $\mathcal{B}_G$ , where

$$S(c, d) = \{\gamma \in B(c, d) : i \bowtie \gamma(i), \forall i \in I(c)\}.$$

REMARK 8.5. Note that  $S(c, d) \neq \emptyset$  if and only if  $c \bowtie d$ . (Recall Subsection 5.1.)

EXAMPLE 8.6. Consider the graph  $G$  of Example 6.3 and the (balanced) equivalence relation  $\bowtie$  on  $\mathcal{C}$  with classes

$$\mathcal{O}_1 = \{1, 2\}, \quad \mathcal{O}_3 = \{3, 4\}, \quad \mathcal{O}_c = \{c\}.$$

Let  $\bar{G} = (\bar{\mathcal{C}}, \bar{\mathcal{E}}, \sim_{\bar{\mathcal{C}}}, \sim_{\bar{\mathcal{E}}})$  be the corresponding natural quotient graph. See Figure 10.

The classes  $\mathcal{O}_1$  and  $\mathcal{O}_3$  are  $c$ -identical and

$$T(c, c) = \{(\text{id}_{I(c)}, c, c), ((13)(24), c, c)\}.$$

Then  $\phi' : T(c, c) \rightarrow \bar{B}(\bar{c}, \bar{c})$  is such that

$$\begin{aligned} \phi'(\text{id}_{I(c)}, c, c) &= (\text{id}_{I(\bar{c})}, \bar{c}, \bar{c}) \\ \phi'((13)(24), c, c) &= ((\bar{1} \bar{3}), \bar{c}, \bar{c}). \end{aligned}$$

We may then state the following.

THEOREM 8.7. Consider a graph  $G$ , a balanced equivalence relation  $\bowtie$  on the nodes of  $G$ , and  $\phi : G \rightarrow \bar{G}$  the quotient map constructed in Subsection 5.3. Then the map  $\phi' : T_G^{\bowtie} \rightarrow \mathcal{B}_{\bar{G}}$  constructed above (Definition 8.3) is a quotient map with kernel  $S_G^{\bowtie}$  (and  $T_G^{\bowtie}/S_G^{\bowtie} \cong \mathcal{B}_{\bar{G}}$ ).

*Proof.* We begin by proving that given any  $c, d \in \mathcal{C}$  such that  $T(c, d) \neq \emptyset$ , and  $(\beta, c, d) \in T(c, d)$ , then the map  $\beta'$  as defined in equation (8.3) is well defined and it is an input isomorphism from  $I(\bar{c})$  to  $I(\bar{d})$ .

Consider as before

$$I(c) = \mathcal{O}_1 \dot{\cup} \dots \dot{\cup} \mathcal{O}_{\bar{n}(c)}$$

and

$$I(d) = \mathcal{O}'_1 \dot{\cup} \dots \dot{\cup} \mathcal{O}'_{\bar{n}(d)}.$$

Since  $T(c, d) \neq \emptyset$  it follows that  $\bar{n}(c) = \bar{n}(d)$ . If  $i, j \in \mathcal{O}_i$ , then  $\bar{i} = \bar{j}$  and  $\beta(i), \beta(j) \in \mathcal{O}'_k$  for some  $k$ , and so  $\beta(\bar{i}) = \beta(\bar{j})$ . Thus (8.3) is well defined. Moreover  $\beta'$  is an input

isomorphism since

$$(\bar{i}, \bar{c}) \sim_{\bar{E}} (\overline{\beta(i)}, \bar{d})$$

if and only if there exists  $\gamma \in B(c, d)$  such that

$$\gamma(\Omega_c(\bar{i})) = \Omega_d(\overline{\beta(i)}).$$

Suppose that  $i \in \mathcal{O}_i$ . Then  $\mathcal{O}_i = \Omega_c(\bar{i})$ . We can take  $\gamma = \beta \in T(c, d)$ , so  $\beta(\Omega_c(\bar{i})) = \beta\mathcal{O}_i = \mathcal{O}'_k$  where  $\beta(i) \in \mathcal{O}'_k$ . Thus  $\mathcal{O}'_k = \Omega_d(\overline{\beta(i)})$ .

The map  $\phi'$  is piecewise-surjective by Theorem 5.5; since  $\phi: G \rightarrow \bar{G}$  is a quotient map, input isomorphisms lift (property (c) of Definition 5.3). Thus the map  $\phi'$  is a quotient map.

To see that  $\ker(\phi') = \mathcal{S}_G^{\boxtimes}$  note that for any  $\gamma \in T(c, d)$  where  $c \boxtimes d$  then  $i \boxtimes \gamma(i)$  for all  $i \in I(c)$ . Thus  $\gamma \in S(c, d)$ ,  $\gamma' = \text{id}_{I(\bar{c})}$  and  $(\gamma, c, d) \in \ker(\phi')$ .  $\square$

Now we develop the analogy with the group-symmetric case. The fixed-point subspace of  $\mathcal{S}_G^{\boxtimes}$  is

$$\text{Fix}(\mathcal{S}_G^{\boxtimes}) = \{x \in P : x_c = x_d \text{ whenever } S(c, d) \neq \emptyset\}.$$

REMARK 8.8. Recall that  $c \boxtimes d$  if and only if  $S(c, d) \neq \emptyset$  since  $\boxtimes$  is balanced. Thus

$$\text{Fix}(\mathcal{S}_G^{\boxtimes}) = \Delta_{\boxtimes}.$$

The elements of  $\mathcal{S}_G^{\boxtimes}$  act as the identity on  $G/\boxtimes$ . In fact, they form the isotropy subgroupoid of any generic element of the polydiagonal  $\Delta_{\boxtimes}$ . (We say that  $x \in \Delta_{\boxtimes}$  is generic when  $x_i = x_j$  if and only if  $i \boxtimes j$ , for all  $i, j \in \mathcal{C}$ .)

In the group-equivariant setting, it is well known and trivial to prove that the fixed-point subspace of any subgroup is mapped to itself by all equivariant mappings. In the groupoid case, an extra technical hypothesis is required.

DEFINITION 8.9. A subgroupoid  $\mathcal{S} = \dot{\bigcup} S(a, b)$  of a groupoid  $\mathcal{B}_G$  is complete if whenever  $\beta(i) = j$  for some morphism  $\beta \in \mathcal{S}$ , then  $S(i, j) \neq \emptyset$ .

EXAMPLE 8.10. Given a subgroupoid  $\mathcal{S} = \dot{\bigcup} S(a, b)$  of a groupoid  $\mathcal{B}_G$ , define  $\boxtimes_{\mathcal{S}}$  by

$$i \boxtimes_{\mathcal{S}} j \iff S(i, j) \neq \emptyset.$$

Then  $\text{Fix}(\mathcal{S}) = \Delta_{\boxtimes_{\mathcal{S}}}$ . If  $\mathcal{S}$  is complete, then  $\boxtimes_{\mathcal{S}}$  is balanced.

REMARK 8.11. Note that  $\mathcal{S}_G^{\boxtimes}$  is complete. This follows from Definition 8.4 and Remark 8.8.

PROPOSITION 8.12. Let  $\mathcal{S}$  be a complete subgroupoid of  $\mathcal{B}_G$ . For any  $f \in \mathcal{F}_G^P$  we have

$$f(\text{Fix}(\mathcal{S})) \subseteq \text{Fix}(\mathcal{S}).$$

Proof. Let  $x \in \text{Fix}(\mathcal{S})$ . That is,  $x_c = x_d$  whenever  $S(c, d) \neq \emptyset$ . We prove that  $f_c(x) = f_d(x)$  whenever  $S(c, d) \neq \emptyset$ . If  $S(c, d) \neq \emptyset$  then there exists  $\beta \in S(c, d)$  such

that  $\beta(c) = d$ . Moreover, because  $\mathcal{S}$  is complete, then  $S(i, \beta(i)) \neq \emptyset$  for all  $i \in I(c)$ . Therefore

$$f_d(x) = f_{\beta(c)}(x) = f_c(\beta^*(x))$$

by  $\mathcal{B}_G$ -equivariance and for each  $i \in I(c)$

$$(\beta^*(x))_i = x_{\beta(i)} = x_i$$

because  $S(i, \beta(i)) \neq \emptyset$  and  $x \in \text{Fix}(\mathcal{S})$ . It follows that  $\beta^*(x) = x$  and thus  $f_d(x) = f_c(x)$ . □

### 8.3. The normalizer viewpoint

How does the symmetry groupoid of the natural quotient graph  $\overline{G}$  relate to that of  $G$ ? As mentioned in the introduction, there is an analogy here with a question in equivariant bifurcation theory. Suppose that  $\Gamma$  is a group acting on  $V$ , that  $f : V \rightarrow V$  is  $\Gamma$ -equivariant, and let  $\Sigma$  be a subgroup of  $\Gamma$ . Then  $f$  leaves  $\text{Fix}(\Sigma)$  invariant, and we can ask which conditions characterize the restriction  $f|_{\text{Fix}(\Sigma)}$ . The most obvious such condition is normalizer-equivariance:  $f|_{\text{Fix}(\Sigma)}$  is  $N(\Sigma)/\Sigma$ -equivariant. See [7, Chapter XIII, Exercise 2.2]. In some cases, this is the only condition required, but in others, ‘hidden symmetries’ impose more complicated conditions.

We now show that something closely analogous happens in the groupoid case. We begin by defining the groupoid analogue of the normalizer of a subgroup.

**DEFINITION 8.13.** Let  $\mathcal{G}$  be a groupoid. The *normalizer* of a subgroupoid  $\mathcal{S}$  of  $\mathcal{G}$  is the largest subgroupoid  $\mathcal{H}$  such that  $\mathcal{S}$  is a normal subgroupoid of  $\mathcal{H}$ .

**LEMMA 8.14.**  $T_G^{\bowtie}$  is the normalizer of  $S_G^{\bowtie}$  in  $\mathcal{B}_G$ .

*Proof.* We prove that if  $\theta \in B(c, d)$  normalizes  $S_G^{\bowtie}$  then  $\theta \in T(c, d)$ . That is, for all  $i, j \in I(c)$  we have  $i \bowtie j$  if and only if  $\theta(i) \bowtie \theta(j)$ .

We have the following.

(i) Given  $\sigma \in B(d, d)$  and  $i \in I(d)$ , then  $\sigma(i) \equiv_d i$ . If also  $\sigma \in S(d, d)$ , then  $\sigma(i) \bowtie i$ . Thus the  $S(d, d)$ -orbits are intersections of  $\bowtie$ -equivalence classes with  $\equiv_d$ -equivalence classes.

(ii) If  $\theta \in B(c, d)$ , then  $\theta$  maps  $\equiv_c$ -equivalence classes into  $\equiv_d$ -equivalence classes. (Recall the structure of  $B(c, d)$  in Subsection 3.2.)

(iii) If  $\theta$  normalizes  $\mathcal{S}$ , then  $\theta$  maps every  $S(c, c)$ -orbit into an  $S(d, d)$ -orbit. This follows from the definition of normal subgroupoid (Subsection 8.1).

From (i)–(iii) it follows that if  $\theta$  normalizes  $\mathcal{S}$ , then  $\theta$  maps  $\bowtie$ -equivalence classes into  $\bowtie$ -equivalence classes. Thus  $\theta \in T(c, d)$ . □

Before providing an example it is convenient to discuss a technical issue: the relation between the symmetry groupoid and the symmetry group of a symmetric graph. When the graph  $G$  has symmetry, the symmetry groupoid  $\mathcal{B}_G$  is *not* the same as the symmetry group  $\Gamma_G$ . However, the two are closely related. In particular, the symmetry group can be interpreted as a subgroupoid of the symmetry groupoid.

Recall that  $\Gamma = \Gamma_G$  acts as a group of permutations of  $\mathcal{C}$ . Define subsets  $\Gamma(c, d) \subseteq \Gamma$  by

$$\Gamma(c, d) = \{\gamma \in \Gamma : \gamma(c) = d\}$$

so that in particular  $\Gamma(c, c)$  is the *stabilizer* of  $c$  in  $\Gamma$ , which is a subgroup. See Neumann *et al.* [14].

PROPOSITION 8.15.

$$\Gamma(c, d)|_{I(c)} \subseteq B(c, d).$$

*Proof.* Check the definitions. Note that technically we must restrict the permutations in  $\Gamma(c, d)$  to the input set  $I(c)$ . □

Note that  $\Gamma(c, d)|_{I(c)}$  may not equal  $B(c, d)$ . If  $G$  has only trivial symmetry,  $\mathcal{B}_G$  may still contain non-trivial  $B(c, d)$ .

The sets of maps  $\Gamma(c, d)|_{I(c)}$ , for all  $c, d \in \mathcal{C}$ , define a groupoid  $\hat{\Gamma}$ . It is possible for  $\mathcal{B}_G$  to be larger than  $\hat{\Gamma}$ . Indeed, this is the interesting case for us.

The main feature of this reformulation of symmetry in terms of groupoid structure is the following.

PROPOSITION 8.16. *A vector field  $f$  on  $P$  satisfying condition (a) of Definition 4.1 is  $\Gamma$ -equivariant, in the usual sense, if and only if it is  $\hat{\Gamma}$ -equivariant.*

*Proof.* This is a simple computation. □

Thus the groupoid formulation encodes the same symmetry information as the symmetry group, but in a different way.

EXAMPLE 8.17. We return to Example 7.10 where  $G$  is a coupled cell graph consisting of five identical cells,  $\mathcal{C} = \{1, 2, 3, 4, 5\}$ , with all-to-all identical coupling. Thus the symmetry groupoid of  $G$  is effectively the group  $\mathbf{S}_5$ . More precisely,  $B(c, d)$  is the set of permutations  $\sigma \in \mathbf{S}_5$  such that  $\sigma(c) = d$ .

Again, we consider the balanced equivalence relation  $\bowtie$  on  $\mathcal{C}$  with classes

$$\{1, 2\}, \{3, 4\}, \{5\}$$

and  $\overline{G} = (\overline{\mathcal{C}}, \overline{\mathcal{E}}, \sim_{\overline{\mathcal{C}}}, \sim_{\overline{\mathcal{E}}})$  the corresponding natural quotient graph. Recall Figure 9.

Suppose that  $\overline{P} = V^5$  where  $V$  is any finite-dimensional vector space. Then

$$\Delta_{\bowtie} = \{(y_1, y_1, y_3, y_3, y_5)\} = \text{Fix}(\mathcal{S}_G^{\bowtie}),$$

where

$$\mathcal{S}_G^{\bowtie} = \mathbf{S}_{\{1,2\}} \times \mathbf{S}_{\{3,4\}}$$

and  $\mathcal{T}_G^{\bowtie}$  is the group generated by  $\mathcal{S}_G^{\bowtie}$  and (13)(24). In fact  $\mathcal{T}_G^{\bowtie}$  is the groupoid corresponding to the the normalizer of  $\mathcal{S}_G^{\bowtie}$  in  $\mathbf{S}_5$ , and

$$\mathcal{T}_G^{\bowtie} / \mathcal{S}_G^{\bowtie} \cong \mathbf{Z}_2,$$

where  $\mathbf{Z}_2$  is the symmetry group of  $\overline{G}$ , interpreted as a groupoid as explained above.

REMARK 8.18. Theorem 7.8 cannot be specialized to the case of  $\Gamma$ -symmetric networks, to provide an analogous theorem for the group-symmetric case. The proof of Proposition 7.11 (which Theorem 7.8 depends on) relies on the direct product structure of symmetric groups of the vertex groups  $B(c, c)$ . (Recall the end of Subsection 3.2.) However, in general, the groups  $\Gamma(c, c)|_{I(c)}$  are not of that type.

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Ana Paula S. Dias  
 Departamento de  
 Matemática Pura  
 Centro de Matemática  
 Universidade do Porto  
 Rua do Campo Alegre, 687  
 4169-007 Porto  
 Portugal  
 apdias@fc.up.pt

Ian Stewart  
 Mathematics Institute  
 University of Warwick  
 Coventry CV4 7AL  
 United Kingdom  
 ins@maths.warwick.ac.uk