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## A first step toward combinatorial pyramids in $nD$ spaces

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*A first step toward combinatorial  
pyramids in  $nD$  spaces*

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# A first step toward combinatorial pyramids in $nD$ spaces

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## Abstract

Combinatorial maps define a general framework which allows to encode any subdivision of an  $nD$  orientable quasi-manifold with or without boundaries. Combinatorial pyramids are defined as stacks of successively reduced combinatorial maps. Such pyramids provide a rich framework which allows to encode fine properties of the objects (either shapes or partitions). Combinatorial pyramids have first been defined in 2D. This first work has latter been extended to pyramids of  $nD$  generalized combinatorial maps. Such pyramids allow to encode stacks of non orientable partitions but at the price of a twice bigger pyramid. These pyramids are also not designed to capture efficiently the properties connected with orientation. The present work presents our first result on the design of an  $nD$  pyramid of combinatorial maps.

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### Note to the reader of [5]

In [5] the authors refer to several lemmas, propositions and their respective proofs which are given in this technical report. A few modifications and corrections have been achieved in this report since the above mentioned conference paper went in press. As a consequence, the numbering of most of the propositions and definitions that are referred to has changed. For that reason, we provide below a table of correspondance between the former numbering, used in [5], and the correct one.

| Reference in [5] | In this version | Page |
|------------------|-----------------|------|
| Definition 16    | Definition 16   | 21   |
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| Proposition 16   | Proposition 13  | 43   |
| Proposition 21   | Proposition 18  | 48   |
| Proposition 22   | Proposition 19  | 49   |
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Table 1

Former definitions, lemmas and propositions numbers and the current ones.

Note also that an index of the definitions, propositions, lemmas and theorems is provided at the end of this report.

## 1 Introduction

Pyramids of combinatorial maps have first been defined in 2D [1], and latter extended to pyramids of  $n$ -dimensional generalized maps by Grasset et al. [7]. Generalized maps model subdivisions of orientable but also non-orientable quasi-manifolds [8] at the expense of twice the data size of the one required for combinatorial maps. For practical use (for example in image segmentation), this may have an impact on the efficiency of the associated algorithms or may even prevent their use. Furthermore, properties and constrains linked to the notion of orientation may be expressed in a more natural way with the formalism of combinatorial maps. For these reasons, we are interested here in the definition of pyramids of  $n$ -dimensional combinatorial maps. This paper is a first step toward the definition of such pyramids, and the link between our definitions and the ones that consider G-maps is maintained throughout the paper. In fact, the link between  $n$ -G-maps and  $n$ -maps was first established by Lienhardt [8] so that it was claimed in [3], but not explicitly stated, that pyramids of  $n$ -maps could be defined.

The key notion for the definition of pyramids of maps is the operation of simultaneous removal or contraction of cells that satisfy some criterions. Thus, we define the operation of simultaneous removal and the one of simultaneous contraction of cells in an  $n$ -map, the latter being introduced here as a removal operation in the dual map.

We first raise in Section 3.1 a minor problem with the definition of "cells with local degree 2 in a G-map" used in [6,3] and more precisely with the criterion for determining if a cell is a valid candidate for removal. We provide a formal definition of the local degree, which is consistent with the results established in the previous papers, using the notion of a *regular cell* that we introduce.

An essential result of this paper, presented in Section 3.1, is that the removal operation we introduce here is well defined since it indeed transforms a map into another map. Instead of checking that the resulting map satisfies from its very definition the properties of a map, we use an indirect proof by using the removal operation in G-maps defined by Damiand in [3,4]. If needed, this way again illustrates the link between the two structures.

Eventually, in Section 3.2 we will state a definition of simultaneous contraction of cells in a G-map in terms of removals in the dual map, definition which we prove to be equivalent to the one given by Damiand and Lienhardt in [3]. We finally define in the same way the simultaneous contraction operation in maps and provide a first result (Proposition 20) that justifies this definition using the latter equivalence.

## 2 Combinatorial maps

### 2.1 Basic definitions

**Definition 1 (*n*-G-map [8])** Let  $n \geq 0$ , an *n*-G-map is defined as an  $n + 2$ -tuple  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  where:

- $\mathcal{D}$  is a finite non-empty set of darts;
- $\alpha_0, \dots, \alpha_n$  are involutions on  $\mathcal{D}$  (i.e.  $\forall i \in \{0, \dots, n\}, \alpha_i^2(b) = b$ ) such that:
  - $\forall i \in \{0, \dots, n - 1\}, \alpha_i$  is an involution without fixed point (i.e.  $\forall b \in \mathcal{D}, \alpha_i(b) \neq b$ );
  - $\forall i \in \{0, \dots, n - 2\}, \forall j \in \{i + 2, \dots, n\}, \alpha_i \alpha_j$  is an involution.

If  $\alpha_n$  is an involution without fixed point,  $G$  is said to be without boundaries or closed. In the following we only consider closed *n*-G-maps with  $n \geq 2$ .

**Remark 1** For any  $i, j \in \{0, \dots, n\}$  such that  $j \geq i + 2$ , the permutation  $\alpha_i \alpha_j$  is an involution. Therefore, in any *n*-G-map we have:

$$\forall i \in \{0, \dots, n - 2\}, \forall j \in \{i + 2, \dots, n\}, \alpha_i \alpha_j = \alpha_j \alpha_i$$

Indeed, if  $\alpha_i \alpha_j \alpha_i \alpha_j = 1_{\mathcal{D}}$ , then  $\alpha_i \alpha_j \alpha_i = \alpha_j^{-1} = \alpha_j$  and  $\alpha_i \alpha_j = \alpha_j \alpha_i^{-1} = \alpha_j \alpha_i$ .

**Definition 2 (*n*-map [8])** An *n*-map ( $n \geq 1$ ) is defined as an  $(n + 1)$ -tuple  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  such that:

- $\mathcal{D}$  is a finite non-empty set of darts;
- $\gamma_0, \dots, \gamma_{n-2}$  are involutions on  $\mathcal{D}$  and  $\gamma_{n-1}$  is a permutation on  $\mathcal{D}$  such that
  - $\forall i \in \{0, \dots, n - 2\}, \forall j \in \{i + 2, \dots, n\}, \gamma_i \gamma_j$  is an involution.

**Definition 3 (Orbit)** Let  $\Phi = \{\phi_1, \dots, \phi_k\}$  be a set of permutations on  $\mathcal{D}$  (a set of darts). We denote by  $\langle \Phi \rangle$  the permutation group generated by  $\Phi$ , i.e. the set of permutations obtained by any composition and inversion of permutations contained in  $\Phi$ . The orbit of a dart  $d \in \mathcal{D}$  relatively to  $\Phi$  is defined by  $\langle \Phi \rangle (d) = \{\phi(d) \mid \phi \in \langle \Phi \rangle\}$ . Furthermore, we extend this notation to the empty set by defining  $\langle \emptyset \rangle$  as the identity map.

**Definition 4 (Connected component)** Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an *n*-map (resp.  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an *n*-G-map). A subset  $\mathcal{D}'$  of  $\mathcal{D}$  is called a connected component of  $M$  (resp.  $G$ ) if  $\mathcal{D}' = \langle \gamma_0, \dots, \gamma_{n-1} \rangle (d)$  (resp.  $\mathcal{D}' = \langle \alpha_0, \dots, \alpha_{n-1} \rangle (d)$ ) for some dart  $d \in \mathcal{D}'$ .

An *n*-map may be associated to an *n*-G-map, as stated by the next definition. In this paper, we use this direct link between the two structures to show that the removal operation we introduce for maps is properly defined (Section 3.1).

For that purpose, we notably use the fact that a removal operation (as defined by Damiand and Lienhardt) in a G-map has a counterpart (according to our definition) in its associated map and vice versa.

**Definition 5 (Map of the hypervolumes)** *Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ -G-map ( $n \geq 1$ ). The  $n$ -map  $HV = (\mathcal{D}, \delta_0 = \alpha_n \alpha_0, \dots, \delta_{n-1} = \alpha_n \alpha_{n-1})$  is called the map of the hypervolumes of  $G$ .*

Lienhardt [9] proved that if the  $n$ -G-map  $G$  is orientable,  $HV$  has two connected components. In the following we only consider orientable  $n$ -G-maps and assume that an arbitrary component of the map  $HV$  is chosen.

**Definition 6 (Dual and inverse)** *Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ -G-map and let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map.*

- The dual of  $G$ , denoted by  $\overline{G}$ , is defined by:

$$\overline{G} = (\mathcal{D}, \alpha_n, \alpha_{n-1}, \dots, \alpha_0)$$

- The dual and the inverse of  $M$  are respectively defined by:

$$\begin{aligned} \overline{M} &= (\mathcal{D}, \gamma_0^{-1}, \gamma_0^{-1} \gamma_{n-1}, \dots, \gamma_0^{-1} \gamma_1) \\ &= (\mathcal{D}, \gamma_0, \gamma_0 \gamma_{n-1}, \dots, \gamma_0 \gamma_1) \\ M^{-1} &= (\mathcal{D}, \gamma_0, \dots, \gamma_{n-2}, \gamma_{n-1}^{-1}) \end{aligned}$$

Note that we also have  $M^{-1} = (\mathcal{D}, \gamma_0^{-1}, \dots, \gamma_{n-2}^{-1}, \gamma_{n-1}^{-1})$  since  $(\gamma_i)_{i \in \{0, \dots, n-2\}}$  is an involution.

**Proposition 1** *If we consider the function  $HV$  which maps each  $n$ -G-map  $G$  to an  $n$ -map of the hypervolumes  $HV(G)$ . We have if  $n > 1$ :*

$$\overline{HV(G)} = HV(\overline{G}).$$

In other words the following diagram commutes:

$$\begin{array}{ccc} G & \xrightarrow{\text{dual}} & \overline{G} \\ HV \downarrow & & \downarrow HV \\ M & \xrightarrow{\text{dual}} & \overline{M} \end{array}$$

*Proof:*

$$G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$$

$$\begin{array}{l|l} HV(G) = (\mathcal{D}, \alpha_n \alpha_0, \dots, \alpha_n \alpha_{n-1}) & \overline{G} = (\mathcal{D}, \alpha_n, \dots, \alpha_0) \\ \hline \overline{HV(G)} = (\mathcal{D}, \alpha_0 \alpha_n, \dots, \alpha_0 \alpha_1) & HV(\overline{G}) = (\mathcal{D}, \alpha_0 \alpha_n, \dots, \alpha_0 \alpha_1) \end{array}$$

Indeed, since  $n > 1$ ,  $\alpha_n \alpha_0 = \alpha_0 \alpha_n$  and  $\forall i \in \{1, \dots, n-1\}$ ,  $\alpha_n \alpha_0 \alpha_n \alpha_i = \alpha_0 \alpha_n \alpha_n \alpha_i = \alpha_0 \alpha_i$ .  $\square$

**Proposition 2 (Associated maps of an  $n$ -G-map [8])** *The two  $n$ -maps associated to an  $n$ -G-map  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  are defined as:*

$$M_1 = HV(G) = (\mathcal{D}, \alpha_n \alpha_0, \alpha_n \alpha_1, \dots, \alpha_n \alpha_{n-1}) \stackrel{not.}{=} (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$$

$$M_2 = \overline{M_1} = HV(\overline{G}) = (\mathcal{D}, \alpha_0 \alpha_n, \alpha_0 \alpha_{n-1}, \dots, \alpha_0 \alpha_1) \stackrel{not.}{=} (\mathcal{D}, \overline{\gamma}_0, \dots, \overline{\gamma}_{n-1})$$

Since there is a one-to-one correspondence between  $i$ -cells<sup>1</sup> of  $M_1$  and  $(n-i)$ -cells of  $M_2 = \overline{M_1}$ , and since there is a direct link between the subscripts of the permutations of a map and the way cells are defined, it is convenient to denote<sup>2</sup>  $(\mathcal{D}, \overline{\gamma}_0, \dots, \overline{\gamma}_{n-1}) \stackrel{not.}{=} (\mathcal{D}, \beta_n, \dots, \beta_1)$ .

Moreover the permutations  $(\beta_i)_{i \in \{1, \dots, n\}}$  and  $(\gamma_i)_{i \in \{0, \dots, n-1\}}$  are related by the following relationships ( $n \geq 2$ ):

$$\gamma_0 = \beta_n \text{ and } \forall i \in \{1, \dots, n-1\} \begin{cases} \gamma_i = \beta_n \beta_i \\ \beta_i = \gamma_0 \gamma_i \end{cases}$$

*Proof:* From Definition 6  $\overline{M_2} = (\mathcal{D}, \beta_n, \beta_n \beta_1, \dots, \beta_n \beta_{n-1})$ . Since  $\overline{M_2} = \overline{\overline{M_1}} = M_1$ , we have  $\gamma_0 = \beta_n$  and  $\forall i \in \{1, \dots, n-1\}$ ,  $\gamma_i = \beta_n \beta_i$ .

In the same way, we have  $\overline{M_1} = (\gamma_0, \gamma_0 \gamma_{n-1}, \dots, \gamma_0 \gamma_1)$ . We also have by Proposition 1,  $\overline{M_1} = \overline{HV(G)} = HV(\overline{G}) = M_2$ . Therefore:

$$\beta_n = \gamma_0 \text{ and } \forall i \in \{1, \dots, n-1\} \beta_i = \gamma_0 \gamma_i$$

$\square$

The two maps  $M_1$  and  $M_2$  associated to an  $n$ -G-map  $G$  are respectively defined as the maps of the hypervolumes of  $G$  and  $\overline{G}$ . However, whenever the reference

<sup>1</sup> Cells are formally defined in subsection 2.3.

<sup>2</sup> These notation are also used for example in [2].



to the  $n$ -G-map will not be required we will simply consider that we have two dual maps describing a same partition of the space. The equivalence between these two representations is illustrated in Fig. 1 where the 2-G-map  $G$  is the triple  $(\mathcal{D} = \mathcal{D}_1 \cup \mathcal{D}_2, \gamma_0, \gamma_1)$  with:

$$\mathcal{D}_1 = \{1, 2, 3, 4, 5, 6\}, \mathcal{D}_2 = \{-1, -2, -3, -4, -5, -6\}$$

$$\alpha_0 = (1, -1)(2, -2)(3, -3)(4, -4)(5, -5)(6, -6)$$

$$\alpha_1 = (-1, -2)(2, -1)(3, -4)(4, -3)(5, -6)(6, -5)$$

$$\alpha_2 = (1, -6)(2, -3)(3, -2)(4, -5)(5, -4)(6, -1)$$

The 2-map  $HV(G)$  is  $(\mathcal{D}_1, \gamma_0, \gamma_1)$  where

$$\gamma_0 = (1, 6)(2, 3)(4, 5)(-1, -6)(-2, -3)(-4, -5)$$

$$\gamma_1 = (1, 5, 3)(2, 4, 6)(-2, -4, -6)(-1, -5, -3)$$

The 2-map  $HV(\bar{G})$  is  $(\mathcal{D}_2, \beta_2, \beta_1)$  where

$$\beta_2 = \gamma_0$$

$$\beta_1 = (1, 2)(3, 4)(5, 6)(-1, -2)(-3, -4)(-5, -6)$$

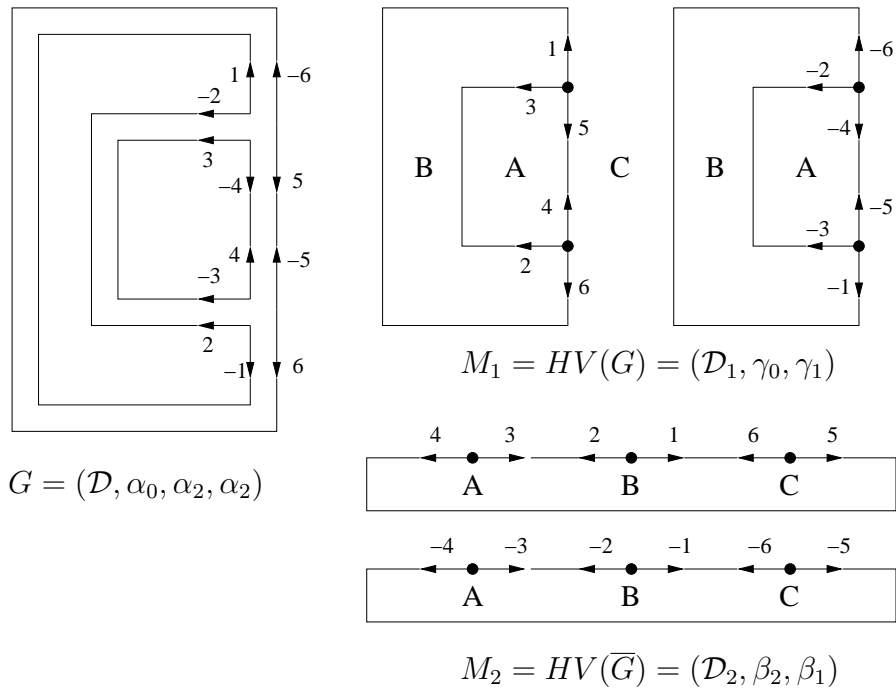


Fig. 1. A closed 2-G-map  $G$  (left). The 2-maps  $HV(G)$  and  $HV(\bar{G})$  (right).

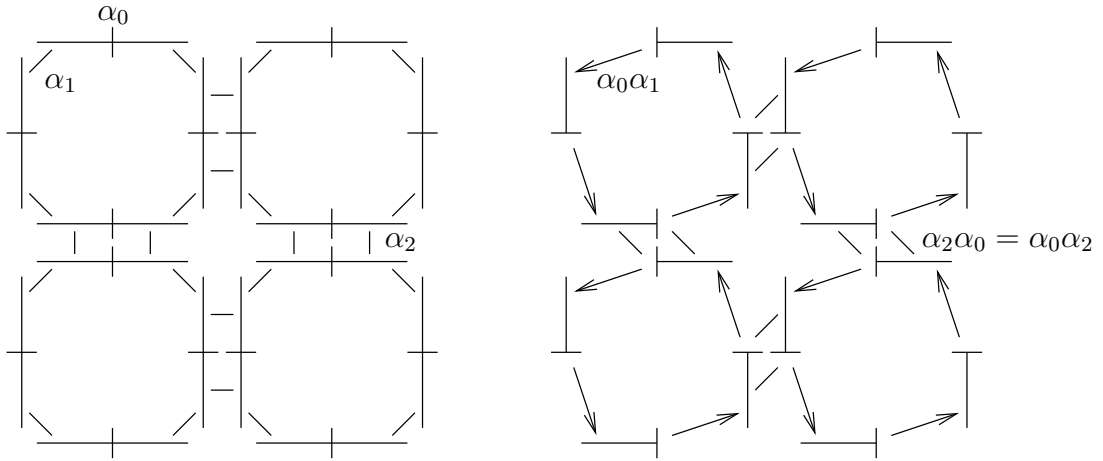


Fig. 2. A part of a closed 2-G-map  $G$  (left) and a part of a connected component of the associated  $n$ -map  $M_2 = HV(\overline{G})$  (right).

## 2.2 From maps to $G$ -maps and vice versa

We first define the notion of an  $n$ -G-map associated to a given  $n$ -map. We need a precise construction scheme of the associated  $G$ -map, since Lienhard's Theorem 4 [8] only stated the existence of such a  $G$ -map.

**Definition 7** Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map. We denote by  $AG(M)$  the  $(n+1)$ -tuple

$$(\tilde{\mathcal{D}}, \alpha_0, \alpha_1, \dots, \alpha_n)$$

where

- $\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}'$ , where  $\mathcal{D}'$  is a finite set with the same cardinal as  $\mathcal{D}$ ,
- $\sigma$  is a one-to-one correspondance between  $\mathcal{D}$  and  $\mathcal{D}'$ .
- $\alpha_i$  is defined for  $i \in \{0, \dots, n-2\}$  by:

$$\alpha_i : \tilde{\mathcal{D}} \longrightarrow \tilde{\mathcal{D}}$$

$$d \longmapsto \begin{cases} d\gamma_i\sigma & \text{if } d \in \mathcal{D} \\ d\sigma^{-1}\gamma_i & \text{if } d \in \mathcal{D}' \end{cases}$$

- $\alpha_{n-1}$  is defined by:

$$\alpha_{n-1} : \tilde{\mathcal{D}} \longrightarrow \tilde{\mathcal{D}}$$

$$d \longmapsto \begin{cases} d\gamma_{n-1}^{-1}\sigma & \text{if } d \in \mathcal{D} \\ d\sigma^{-1}\gamma_{n-1} & \text{if } d \in \mathcal{D}' \end{cases}$$

- $\alpha_n$  is defined by:

$$\alpha_n : \tilde{\mathcal{D}} \longrightarrow \tilde{\mathcal{D}}$$

$$d \longmapsto \begin{cases} d\sigma & \text{if } d \in \mathcal{D} \\ d\sigma^{-1} & \text{if } d \in \mathcal{D}' \end{cases}$$

**Remark 2** Any map  $\alpha_i$  of Definition 7 satisfies:

$$\begin{aligned} \alpha_{i|\mathcal{D}} : \mathcal{D} &\longrightarrow \mathcal{D}' \\ \alpha_{i|\mathcal{D}'} : \mathcal{D}' &\longrightarrow \mathcal{D} \end{aligned} \tag{1}$$

Furthermore,  $\alpha_{i|\mathcal{D}}$  and  $\alpha_{i|\mathcal{D}'}$  are both one-to-one correspondances, as the composition of bijective maps for  $i < n$ , and from the very definition of  $\alpha_n$ .

**Lemma 1** If  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  is an  $n$ -map and  $AG(M) = (\tilde{\mathcal{D}}, \alpha_0, \dots, \alpha_n)$ . For all  $i \in \{0, \dots, n-1\}$  we have  $(\alpha_n \alpha_i)|_{\mathcal{D}} = \gamma_i$ . We also have  $(\alpha_0 \alpha_n)|_{\mathcal{D}} = \gamma_0$  and for all  $i \in \{1, \dots, n-1\}$  and  $(\alpha_0 \alpha_i)|_{\mathcal{D}} = \gamma_0 \gamma_i$ .

*Proof:* This comes from the very definition of the involutions  $\alpha_i$ ,  $i \in \{0, \dots, n\}$  (Definition 7). Indeed, let  $d$  be a dart of  $\mathcal{D}$ , we have  $d\alpha_j \in \mathcal{D}'$  for all  $j \in \{0, \dots, n\}$ .

If  $i \in \{0, \dots, n-1\}$ , by Definition 7 we obtain that  $d\alpha_n \alpha_i = d\sigma\sigma^{-1}\gamma_i = d\gamma_i$ . We also have  $d\alpha_0 \alpha_n = d\gamma_0\sigma\sigma^{-1} = d\gamma_0$ . In the last case, if  $i \in \{1, \dots, n-1\}$  we have  $d\alpha_0 \alpha_i = d\gamma_0\sigma\sigma^{-1}\gamma_i = d\gamma_0\gamma_i$ .  $\square$

**Proposition 3** For any  $n$ -map  $M$ ,  $AG(M)$  is an  $n$ -G-map.

*Proof:* We show that  $AG(M)$  satisfies the properties of G-maps (Definition 1). The set  $\tilde{\mathcal{D}}$  is indeed finite and non-empty, so we need to check that the applications  $\alpha_i$  from  $\mathcal{D}'$  to  $\mathcal{D}$  are involutions that satisfy the conditions given by the definition.

For  $i \in \{0, \dots, n\}$ , following Remark 2 and the fact that:

- $\mathcal{D} \cap \mathcal{D}' = \emptyset$ , and
- the maps  $\alpha_{i|\mathcal{D}}$  and  $\alpha_{i|\mathcal{D}'}$  are one-to-one

we conclude that  $\alpha_i$  is one-to-one. Indeed, if  $d_1\alpha_i = d_2\alpha_i$  for  $d_1, d_2 \in \tilde{\mathcal{D}}$ , it follows from (1) that either  $\{d_1, d_2\} \subset \mathcal{D}$  or  $\{d_1, d_2\} \subset \mathcal{D}'$ . In both cases, it implies that  $d_1 = d_2$  since  $\alpha_{i|\mathcal{D}}$  (resp.  $\alpha_{i|\mathcal{D}'}$ ) is a one-to-one map.

Now, let  $d \in \tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}'$ . Either  $d \in \mathcal{D}$  or  $d \in \mathcal{D}'$ . In either case, by (1) and the fact that  $\alpha_{i|\mathcal{D}}$  and  $\alpha_{i|\mathcal{D}'}$  are onto, there exists  $b \in \tilde{\mathcal{D}}$  such that  $d = b\alpha_i$ . The map  $\alpha_i$  is therefore onto.

Let us additionally remark that the preimage of  $b$  may be explicited. Indeed, if  $i < n - 1$  we have  $b = d\gamma_i\sigma$  if  $d \in \mathcal{D}$  and  $b = d\sigma\gamma_i$  if  $d \in \mathcal{D}'$ . For  $i = n - 1$  we have  $b = d\gamma_{n-1}\sigma$  if  $d \in \mathcal{D}$  and  $b = d\sigma\gamma_{n-1}^{-1}$  if  $d \in \mathcal{D}'$ . For  $i = n$ ,  $b = d\sigma^{-1}$  if  $d \in \mathcal{D}$  and  $b = d\sigma$  if  $d \in \mathcal{D}'$ .

Eventually, the maps  $\alpha_i$  are both one-to-one and onto, so they are permutations of  $\tilde{\mathcal{D}}$ . Let us check that they are involutions.

The map  $\alpha_n$  is an involution since  $d\alpha_n^2$  is either equal to  $d\sigma\sigma^{-1} = d$  (if  $d \in \mathcal{D}$ ) or to  $d\sigma^{-1}\sigma = d$  (if  $d \in \mathcal{D}'$ ).

For  $i = n - 1$ , we have  $d\alpha_i^2 = d\gamma_{n-1}^{-1}\sigma\sigma^{-1}\gamma_{n-1}$  or  $d\alpha_i = d\sigma^{-1}\gamma_{n-1}\gamma_{n-1}^{-1}\sigma$ , which in both cases is equal to  $d$ , so  $\alpha_{n-1}$  is an involution.

If  $i < n - 1$ , from the definition of  $\alpha_i$  we have  $d\alpha_i\alpha_i = d\gamma_i\sigma\sigma^{-1}\gamma_i$  if  $d \in \mathcal{D}$  since in this case  $d\gamma_i\sigma \in \mathcal{D}'$ . Since  $\gamma_i$ ,  $i < n - 1$  is an involution we obtain  $d\alpha_i\alpha_i = d$ , so  $\alpha_i$  is an involution. (The case when  $d \in \mathcal{D}'$  is similar.)

We conclude that all the maps  $\alpha_i$  are involutions on  $\tilde{\mathcal{D}}$ . It is also readily seen from (1) and the fact that  $\mathcal{D} \cap \mathcal{D}' = \emptyset$  that these maps have no fixed points.

Now, we need to check that for all  $i \in \{0, \dots, n - 2\}$  and all  $j \in \{i + 2, \dots, n\}$ ,  $\alpha_i\alpha_j$  is an involution. For that purpose, we simply follow Definition 7 to build the following table. The two last columns show that the equality holds for any possible value of  $i$  and  $j$ .

| $i$       | $j$       | $d \in$        | $d\alpha_i\alpha_j$   | $d\alpha_j\alpha_i$   |
|-----------|-----------|----------------|---|---|
| $< n - 1$ | $n$       | $\mathcal{D}$  | $d\gamma_i\sigma\sigma^{-1} = \gamma_i$                         | $d\sigma\sigma^{-1}\gamma_i = \gamma_i$                                   |
| $< n - 1$ | $n$       | $\mathcal{D}'$ | $d\sigma^{-1}\gamma_i\sigma$                                    | $d\sigma^{-1}\gamma_i\sigma$  |
| $< n - 2$ | $n - 1$   | $\mathcal{D}$  | $d\gamma_i\sigma\sigma^{-1}\gamma_{n-1} = \gamma_i\gamma_{n-1}$ | $d\gamma_{n-1}^{-1}\sigma\sigma^{-1}\gamma_i = \gamma_{n-1}^{-1}\gamma_i$ |
| $< n - 2$ | $n - 1$   | $\mathcal{D}'$ | $d\sigma^{-1}\gamma_i\gamma_{n-1}^{-1}\sigma$                   | $d\sigma^{-1}\gamma_{n-1}^{-1}\gamma_i\sigma$                             |
| $< n - 3$ | $< n - 1$ | $\mathcal{D}$  | $d\gamma_i\sigma\sigma^{-1}\gamma_j = \gamma_i\gamma_j$         | $d\gamma_j\sigma\sigma^{-1}\gamma_i = \gamma_j\gamma_i$                   |
| $< n - 3$ | $< n - 1$ | $\mathcal{D}'$ | $d\sigma^{-1}\gamma_i\gamma_j\sigma$                            | $d\sigma^{-1}\gamma_j\gamma_i\sigma$                                      |

In the last four rows of the table, we simply use the fact that  $\gamma_i\gamma_j = \gamma_j\gamma_i$  (since  $M$  is an  $n$ -map) to conclude that  $d\alpha_i\alpha_j = d\alpha_j\alpha_i$ .

The overall conclusion is that  $AG(M)$  is indeed an  $n$ -G-map.  $\square$

**Remark 3** If  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  is an  $n$ -map and  $\mathcal{D}'$  is a subset of  $\mathcal{D}$  such that for all  $d \in \mathcal{D}'$  and all  $i \in \{0, \dots, n - 1\}$ ,  $d\gamma_i \in \mathcal{D}'$ ; then the map  $\gamma_j|_{\mathcal{D}'}$  is well defined for all  $j \in \{0, \dots, n - 1\}$  and the  $(n - 1)$ -tuple  $M' =$

$(\mathcal{D}', \gamma_{0|\mathcal{D}'}, \dots, \gamma_{n-1|\mathcal{D}'})$  satisfies all the conditions of Definition 2.

Using the next lemma, it follows from the latter remark that  $M'$  is a valid  $n$ -map if and only if  $\mathcal{D}'$  is the union of connected components of  $M$ , which leads to the notion of induced sub-map (Definition 8).

**Lemma 2** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and  $\mathcal{D}'$  be a subset of  $\mathcal{D}$ . The two following properties are equivalent:*

- i)  $\mathcal{D}'$  is a union of connected components of  $M$ ;*
- ii)  $\forall d \in \mathcal{D}', \forall i \in \{0, \dots, n-1\}, d\gamma_i \in \mathcal{D}'$ .*

*Proof:* ( $i \Rightarrow ii$ ) since  $d\gamma_i$  belongs to the same connected component of  $M$  as  $d$ , thus it belongs to  $\mathcal{D}'$  if  $d \in \mathcal{D}'$ .

( $ii \Rightarrow i$ ) Let  $\mathcal{R}$  be the relation on  $\mathcal{D}'$  defined by

$$d\mathcal{R}d' \Leftrightarrow \exists i, d\gamma_i = d'$$

It is readily seen that the reflexive and transitive closure of  $\mathcal{R}$  is an equivalence relation whose equivalence classes are orbits in  $M$  that use all the permutations  $\gamma$ 's, i.e. they are connected components of  $M$ . Using  $ii$ ),  $\mathcal{D}'$  is such an equivalent class.  $\square$

**Definition 8** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and  $\mathcal{D}'$  be a union of connected components of  $\mathcal{D}$ . The  $n$ -map  $(\mathcal{D}', \gamma_{0|\mathcal{D}'}, \dots, \gamma_{n-1|\mathcal{D}'})$ , following Remark 3, is called the sub-map of  $M$  induced by  $\mathcal{D}'$ , which we denote by  $M|_{\mathcal{D}'}$ .*

In the same way, the notion of a sub-map of an  $n$ -G-map is used in the sequel. Its definition is similar.

**Proposition 4** *If  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$ , then we have  $M = HV(AG(M))|_{\mathcal{D}}$ .*

*Proof:* Let us consider the following (G-)maps:

- $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$
- $G = AG(M) = (\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}', \alpha_0, \dots, \alpha_n)$
- $HV(G) = (\tilde{\mathcal{D}}, \gamma'_0, \dots, \gamma'_{n-1})$

following Definitions 7 and 5.

We first prove that for all  $d \in \mathcal{D}$  and all  $i \in \{0, \dots, n-1\}$ ,  $d\gamma'_i = d\gamma_i$ . In other word, we prove that  $\gamma'_{i|\mathcal{D}} = \gamma_i$ . Indeed, by Definition 5 and Definition 7, we

have for all  $d \in \mathcal{D}$ :

$$\begin{aligned}
\text{If } i = n - 1, \quad d\gamma'_{n-1} &= d\alpha_n\alpha_{n-1} && \text{(Definition 5)} \\
&= d\sigma\sigma^{-1}\gamma_{n-1} = d\gamma_{n-1} && \text{(Definition 7)} \\
\text{if } i < n - 1, \quad d\gamma'_i &= d\alpha_n\alpha_i && \text{(Definition 5)} \\
&= d\sigma\sigma^{-1}\gamma_i = d\gamma_i && \text{(Definition 7)}
\end{aligned}$$

Let  $b$  be a dart of  $\mathcal{D}$ . Since  $M$  is connected, we have  $\mathcal{D} = \langle \gamma_0, \dots, \gamma_{n-1} \rangle (b)$ . If  $d$  is a dart of  $\mathcal{D}$  we may thus write  $d = b\gamma_{h_1} \dots \gamma_{h_p}$ , with  $p \in \mathbb{N}$  and  $h_k \in \{0, \dots, n-1\}$  for  $k \in \{1, \dots, p\}$ . Since  $\gamma_i = \gamma'_{i|\mathcal{D}}$ , we may prove by a simple recurrence on  $p$  that  $b\gamma_{h_1} \dots \gamma_{h_p} = b\gamma'_{h_1} \dots \gamma'_{h_p}$  and we deduce that  $\mathcal{D} \subset \langle \gamma'_0, \dots, \gamma'_{n-1} \rangle (b)$  in  $G$ . On the other hand, if  $d \in \langle \gamma'_0, \dots, \gamma'_{n-1} \rangle (b)$ , we have  $d = b\gamma'_{h_1} \gamma'_{h_2} \dots \gamma'_{h_q}$  with  $q \in \mathbb{N}$  and  $h_k \in \{0, \dots, n-1\}$  for  $k \in \{1, \dots, q\}$ , and it is again readily seen by a recurrence on  $q$  that  $d = b\gamma_{h_1} \gamma_{h_2} \dots \gamma_{h_q}$ , thus  $d \in \mathcal{D}$ . Eventually, we have  $\mathcal{D} = \langle \gamma'_0, \dots, \gamma'_{n-1} \rangle (b)$  (in  $G$ ).

The orbit  $\mathcal{D} = \langle \gamma'_0, \dots, \gamma'_{n-1} \rangle (b)$ , which uses all the permutations of  $HV(G)$ , is then a connected component of  $\tilde{\mathcal{D}}$  in  $G$ . Therefore, since  $\gamma'_{i|\mathcal{D}} = \gamma_i$ , we obtain that  $M = (\mathcal{D}, \gamma'_{0|\mathcal{D}}, \dots, \gamma'_{n-1|\mathcal{D}})$  is one of the  $n$ -maps induced by the connected component  $\langle \gamma'_0, \dots, \gamma'_{n-1} \rangle (b)$  of  $HV(G)$ . In other words,  $M = HV(G)_{|\mathcal{D}}$ .  $\square$

### 2.3 Cells in maps

**Definition 9 ( $n$ -G-maps and cells [8])** Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ - $G$ -map ( $n \geq 1$ ). Let us consider  $d \in \mathcal{D}$ . The  $i$ -cell, or cell of dimension  $i$ , which contains  $d$  is denoted by  $\mathcal{C}_i(d)$  and defined by the orbit:

$$\mathcal{C}_i(d) = \langle \alpha_0, \dots, \hat{\alpha}_i, \dots, \alpha_n \rangle (d)$$

where  $\hat{\alpha}_i$  denotes the absence of the involution  $\alpha_i$ .

**Definition 10 ( $n$ -maps and cells [8])** Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map. The  $i$ -cell or cell of dimension  $i$  (vertex, edges, ...) of  $M$  which owns a given dart  $d \in \mathcal{D}$  is denoted by  $\mathcal{C}_i(d)$  and defined by the orbits:

$$\forall i \in \{0, \dots, n-1\} \quad \mathcal{C}_i(d) = \langle \gamma_0, \dots, \hat{\gamma}_i, \dots, \gamma_{n-1} \rangle (d)$$

$$\text{For } i = n \quad \mathcal{C}_n(d) = \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-1} \rangle (d)$$

In both an  $n$ -map and an  $n$ - $G$ -map, two cells  $\mathcal{C}$  and  $\mathcal{C}'$  with different dimensions will be called *incident* if  $\mathcal{C} \cap \mathcal{C}' \neq \emptyset$ .

**Proposition 5** *The cells of the map  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  may be equivalently expressed according to the permutations of  $\overline{M} = (\mathcal{D}, \beta_n, \dots, \beta_1)$  using the following equations:*

$$\begin{aligned} \text{For } i = 0 \quad \mathcal{C}_0(d) &= \langle \beta_1^{-1}\beta_2, \dots, \beta_1^{-1}\beta_n \rangle(d) \\ \forall i \in \{1, \dots, n\} \quad \mathcal{C}_i(d) &= \langle \beta_0, \dots, \hat{\beta}_i, \dots, \beta_n \rangle(d) \end{aligned}$$

*Proof:* Using Proposition 2, we have for any  $i \in \{2, \dots, n-1\}$ ,  $\beta_1^{-1}\beta_i = \gamma_1^{-1}\gamma_0\gamma_0\gamma_i = \gamma_1^{-1}\gamma_i$ . Moreover,  $\beta_1^{-1}\beta_n = \gamma_1^{-1}\gamma_0\gamma_0 = \gamma_1^{-1}$ . We have thus:

- For  $i = 0$ ,

$$\begin{aligned} \mathcal{C}_0(d) &= \langle \gamma_1, \gamma_2, \dots, \gamma_{n-1} \rangle(d) \\ &= \langle \beta_n\beta_1, \beta_n\beta_2, \dots, \beta_n\beta_{n-1} \rangle(d) \\ &= \langle \beta_1^{-1}\beta_n, \beta_n\beta_2, \dots, \beta_n\beta_{n-1} \rangle(d) \\ &= \langle \beta_1^{-1}\beta_n, \beta_1^{-1}\beta_2, \dots, \beta_1^{-1}\beta_{n-1} \rangle(d) \\ &= \langle \beta_1^{-1}\beta_2, \dots, \beta_1^{-1}\beta_{n-1}, \beta_1^{-1}\beta_n \rangle(d) \end{aligned}$$

- For  $i \in \{1, \dots, n-1\}$ ,

$$\begin{aligned} \mathcal{C}_i(d) &= \langle \gamma_0, \gamma_1, \dots, \gamma_{i-1}, \gamma_{i+1}, \dots, \gamma_{n-1} \rangle(d) \\ &= \langle \gamma_0, \gamma_0\gamma_1, \dots, \gamma_0\gamma_{i-1}, \gamma_0\gamma_{i+1}, \dots, \gamma_0\gamma_{n-1} \rangle(d) \\ &= \langle \beta_n, \beta_1, \dots, \beta_{i-1}, \beta_{i+1}, \dots, \beta_{n-1} \rangle(d) \\ &= \langle \beta_1, \dots, \beta_{i-1}, \beta_{i+1}, \dots, \beta_{n-1}, \beta_n \rangle(d) \end{aligned}$$

- For  $i = n$ ,

$$\begin{aligned} \mathcal{C}_n(d) &= \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-2}, \gamma_0\gamma_{n-1} \rangle(d) \\ &= \langle \beta_1, \dots, \beta_{n-2}, \beta_{n-1} \rangle(d) \end{aligned}$$

□

**Definition 11 (Degree and dual degree of a cell)** *Let  $\mathcal{C}$  be an  $i$ -cell in an  $n$ -( $G$ -)map,  $0 \leq i \leq n$ .*

- *The degree of  $\mathcal{C}$  is the number of  $(i+1)$ -cells incident to  $\mathcal{C}$ .*
- *The dual degree of  $\mathcal{C}$  is the number of  $(i-1)$ -cells incident to  $\mathcal{C}$ .*

**Notation 1** *Let  $(\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ - $G$ -map. For  $d \in \mathcal{D}$ , we denote by  $\langle \hat{\alpha}_{k_1}, \hat{\alpha}_{k_2}, \dots, \hat{\alpha}_{k_p} \rangle(d)$ , where all the involutions are excluded, the orbit  $\langle \Phi \rangle(d)$  where  $\Phi = \{\alpha_0, \dots, \alpha_n\} \setminus \{\alpha_{k_1}, \alpha_{k_2}, \dots, \alpha_{k_p}\}$ .*

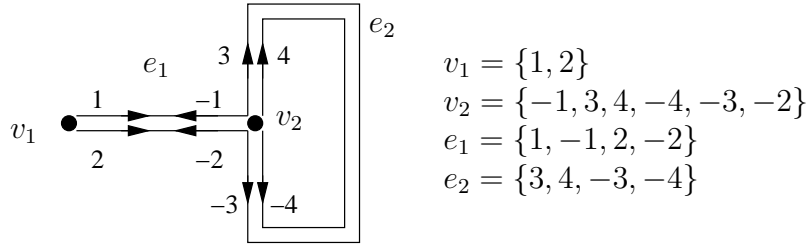


Fig. 3. Degree and local degree: The cell  $v_2$  has a degree 2 and a local degree 3. Dual degree and dual local degree: The cell  $e_1$  has a dual degree and a dual local degree 2, whereas  $e_2$  has a dual degree 1 and a dual local degree 2.

**Property 1** *Following Definition 11, the degree of a cell  $\mathcal{C}$  in an  $n$ -G-map  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  is precisely the number of sets in the set  $\Delta = \{ \langle \hat{\alpha}_{i+1} \rangle (d) \mid d \in \mathcal{C} \}$ .*

*Proof:* This characterization is a direct consequence of the definition of the degree (Definition 11) and the one of an  $(i+1)$ -cell in a G-map (Definition 9).  $\square$

**Definition 12 (Local degree in G-maps)** *Let  $\mathcal{C}$  be an  $i$ -cell in an  $n$ -G-map.*

- For  $i \in \{0, \dots, n-1\}$ , the local degree of  $\mathcal{C}$  is the number

$$|\{ \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b), b \in \mathcal{C} \}|$$

- For  $i \in \{1, \dots, n\}$ , the dual local degree of  $\mathcal{C}$  is the number

$$|\{ \langle \hat{\alpha}_{i-1}, \hat{\alpha}_i \rangle (b), b \in \mathcal{C} \}|$$

*Le local degree (resp. dual local degree) of an  $n$ -cell (resp. a 0-cell) is 0.*

More intuitively, the local degree of an  $i$ -cell  $\mathcal{C}$  is the number of  $i+1$ -cells that locally appear to be incident to  $\mathcal{C}$ . It is called *local* because it may be different from the degree since an  $i+1$ -cell may be incident more than once to an  $i$ -cell, as illustrated in Figure 3 where the 1-cell  $e_2$  is multi-incident to the 0-cell  $v_2$ .

On the other hand, the dual local degree of an  $i$ -cell  $\mathcal{C}$  is the number of  $(i-1)$ -cells that appear to be incident to  $\mathcal{C}$ . As in the example given in Figure 3 where the edge  $e_2$  locally appears to be bounded by two vertices, as it is always the case for a 1-cell, whereas the darts involved by the orbits considered in Definition 12 all belong to a unique vertex ( $v_2$ ).

**Property 2** *The degree of a cell in an  $n$ -G-map is greater than zero and less than or equal to its local degree.*



*Proof:* Let  $\mathcal{C}$  be an  $i$ -cell,  $i \leq n - 1$ , in an  $n$ -G-map and  $d \in \mathcal{C}$ . Following Definition 9,  $\mathcal{C}_{i+1}(d)$  is not empty and  $d \in \mathcal{C} \cap \mathcal{C}_{i+1}(d)$ . Thus,  $\mathcal{C}$  is incident to at least one  $(i + 1)$ -cell.

The degree of  $\mathcal{C}$  is the number  $|\Delta|$  where  $\Delta = \{ \langle \hat{\alpha}_{i+1} \rangle (d) \mid d \in \mathcal{C} \}$  (Property 1). By Definition 12, the local degree of  $\mathcal{C}$  is the number of sets in the set  $\Lambda = \{ \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d) \mid d \in \mathcal{C} \}$ .

Now, for any dart  $b$  of  $\mathcal{C}$  we have  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) \subset \langle \hat{\alpha}_{i+1} \rangle (b)$  (by the definition of an orbit).

Let  $b$  and  $b'$  be darts of  $\mathcal{C}$  such that  $\langle \hat{\alpha}_{i+1} \rangle (b')$  and  $\langle \hat{\alpha}_{i+1} \rangle (b)$  are distinct orbits. Necessarily, we have  $b \notin \langle \hat{\alpha}_{i+1} \rangle (b')$ . Since  $b \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b)$  we deduce that  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) \not\subset \langle \hat{\alpha}_{i+1} \rangle (b')$ . As  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) \subset \langle \hat{\alpha}_{i+1} \rangle (b)$  it follows that this inclusion relation allows to associate each orbit of  $\Lambda$  with exactly one orbit of  $\Delta$ , thus to define a map from  $\Lambda$  to  $\Delta$ . Furthermore, the inclusion  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) \subset \langle \hat{\alpha}_{i+1} \rangle (b)$  also implies that this map is onto. From the existence of such a map we deduce that  $|\Delta| \leq |\Lambda|$ .  $\square$

**Property 3 (Cell with local degree 1)** *An  $i$ -cell  $\mathcal{C}$  in an  $n$ -G-map is of local degree 1 if and only if for all  $d \in \mathcal{C}$ ,  $d\alpha_{i+1} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$ .*

*Proof:* If  $\mathcal{C}$  is of local degree 1, we have  $|\{ \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d) \mid d \in \mathcal{C} \}| = 1$ . It follows that  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d) = \mathcal{C}$  for all  $d \in \mathcal{C}$ . From the definition of an  $i$ -cell,  $d\alpha_{i+1} \in \mathcal{C}$  so that  $d\alpha_{i+1} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$ , hence the “only if” part.

If  $d\alpha_{i+1} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$  for all  $d \in \mathcal{C}$ , it is readily seen that

$$\forall b \in \mathcal{C}, \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) = \langle \hat{\alpha}_i \rangle (b)$$

Indeed, in  $b' = b\alpha_{k_1} \dots \alpha_{k_p} \in \langle \hat{\alpha}_i \rangle (b)$  any involution  $\alpha_{k_j} = \alpha_{i+1}$  may be replaced by a composition of involutions in  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle$  since  $b\alpha_{k_1} \dots \alpha_{k_{j-1}} \in \mathcal{C}$ . Thus we have  $\langle \hat{\alpha}_i \rangle (b) \subset \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b)$ , and obviously  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) \subset \langle \hat{\alpha}_i \rangle (b)$ . Hence the “if” part.  $\square$

The following definition for a cell  $\mathcal{C}$  with a local degree 2 is given in [6].

**Definition 13 (Cell with local degree 2 [6])**

- For all  $i \in \{0, \dots, n - 2\}$ , an  $i$ -cell  $\mathcal{C}$  is of local degree two if

$$\forall b \in \mathcal{C}, b\alpha_{i+1}\alpha_{i+2} = b\alpha_{i+2}\alpha_{i+1}$$

- For all  $i \in \{2, \dots, n\}$ , an  $i$ -cell  $\mathcal{C}$  is of dual local degree two if

$$\forall b \in \mathcal{C}, b\alpha_{i-1}\alpha_{i-2} = b\alpha_{i-2}\alpha_{i-1}$$

In fact, according to the above definition, the 0-cell  $v_1$  in Figure 3 would have a local degree of 2, although this is obviously not what was meant by the authors in their definition. Beside the fact that this definition does not distinguish cells with local degree 1 from cells with local degree 2, it is also far more restrictive than our definition for a cell with local degree 2 (Definition 12).

However, Grasset's definition was intended to characterize cells that could be removed from a G-map, producing a valid new G-map. To that extent, and except for the case of cells with a local degree 1, it is a good criterion but again not a proper definition for cells with local degree 2. (The removal operation in maps is the purpose of Section 3.)

For clarity, we introduce here a criterion for a cell to be *removable*. This criterion may be expressed as a modified version of Grasset's definition for the local degree 2 that actually excludes cells with a local degree 1. But we also provide an equivalent characterization, in terms of several conditions among which appears clearly the exact notion of local degree 2 (Theorem 1).

**Lemma 3** *For any  $i \in \{0, \dots, n-2\}$ , and any  $i$ -cell  $\mathcal{C}$  if:*

- i)  $\exists b \in \mathcal{C}$ ,  $b\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(b)$ , and*
- ii)  $\forall b \in \mathcal{C}$ ,  $b\alpha_{i+1}\alpha_{i+2} = b\alpha_{i+2}\alpha_{i+1}$*

*then  $\mathcal{C}$  is of local degree 2.*

*Proof:* Let  $\mathcal{C}$  be an  $i$ -cell that satisfies conditions *i)* and *ii)*. Let  $b \in \mathcal{C}$  be a dart such that  $b\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(b)$ , following condition *i)*. Eventually, let  $d$  be any other dart of  $\mathcal{C}$ .

From the definition of a cell, we have  $d = b\alpha_{k_1}\alpha_{k_2} \dots \alpha_{k_p}$  with  $k_h \neq i$  for all  $h \in \{1, \dots, p\}$ .

For all  $h > 1$  such that  $k_h = i+1$ , let us consider  $d' = b\alpha_{k_1} \dots \alpha_{k_{h-2}}$ . If  $k_{h-1} = i+2$  then from condition *ii)* we know that  $d'\alpha_{k_{h-1}}\alpha_{k_h} = d'\alpha_{k_h}\alpha_{k_{h-1}}$ . In the remaining cases ( $k_{h-1} \notin \{i, i+2\}$ ) we have either  $|k_h - k_{h-1}| > 1$  or  $k_h = k_{h-1}$ , so that in both cases  $d'\alpha_{k_{h-1}}\alpha_{k_h} = d'\alpha_{k_h}\alpha_{k_{h-1}}$  (see Definition 1 when  $|k_h - k_{h-1}| > 1$ ). In other words,  $\alpha_{i+1}$  always commutes with its predecessor in the sequence of compositions  $\alpha_{k_1}\alpha_{k_2} \dots \alpha_{k_p}$ .

It follows that we may write  $d = b\alpha_{i+1}^r\alpha_{k'_1}\alpha_{k'_2} \dots \alpha_{k'_q}$  with  $k'_h \notin \{i, i+1\}$  for all  $h \in \{1, \dots, q\}$  and  $r \in \mathbb{N}$ . Eventually, if  $r$  is even we have  $d = (b)\alpha_{k'_1}\alpha_{k'_2} \dots \alpha_{k'_q}$  and if  $r$  is odd,  $d = (b\alpha_{i+1})\alpha_{k'_1}\alpha_{k'_2} \dots \alpha_{k'_q}$ . In other words,

$$d \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(b)$$

or

$$d \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(b\alpha_{i+1}).$$

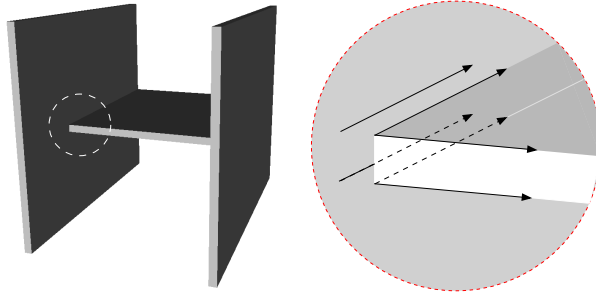


Fig. 4. A solid representation of a part of a 3-G-map where a vertex has a local degree 2 but is not regular. (The vertex is made of all the depicted darts.)

Since  $b\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(b)$ , it follows that the two above orbits are distinct. As any dart  $d \in \mathcal{C}$  belongs to one of them, they form a partition of  $\mathcal{C}$  and the local degree of  $\mathcal{C}$  is 2 according to Definition 12.  $\square$

At this point, we introduce the notion of a regular cell that will help us to clarify (with Theorem 1) the link between the proper notion of a local degree 2 and the one of cells that may indeed be removed while preserving the properties of a G-map.

**Definition 14 (Regular cell)** *An  $i$ -cell ( $i \leq n - 2$ ) in an  $n$ -G-map is said to be regular if it satisfies the two following conditions:*

- a)  $\forall d \in \mathcal{C}, d\alpha_{i+1}\alpha_{i+2} = d\alpha_{i+2}\alpha_{i+1}$  or  $d\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d\alpha_{i+2}\alpha_{i+1})$ ,  
and
- b)  $\forall b \in \mathcal{C}, b\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(b)$

Note that condition a) of the above definition may be read as an implication, in other words:

$$\forall d \in \mathcal{C}, \text{ if } d\alpha_{i+1}\alpha_{i+2} \neq d\alpha_{i+2}\alpha_{i+1} \text{ then } d\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d\alpha_{i+2}\alpha_{i+1})$$

As an illustration, Figure 4 depicts a vertex with local degree 2 in a 3-G-map, vertex which is not regular according to the above definition. Following Grasset et al.'s criterion, such a vertex is not considered as removable because it does not have a local degree two (according to their definition of the local degree). In our case, this vertex actually has a local degree two but is still excluded because it is not regular.

**Lemma 4** *Let  $G$  be an  $n$ -G-map and  $\mathcal{C}$  be an  $i$ -cell of  $G$  for  $i \in \{0, \dots, n-2\}$ . If both conditions i) and ii) below are satisfied,*

- i)  $\exists b \in \mathcal{C}, b\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(b)$ , and
- ii)  $\forall b \in \mathcal{C}, b\alpha_{i+1}\alpha_{i+2} = b\alpha_{i+2}\alpha_{i+1}$

then  $\mathcal{C}$  is regular.

*Proof:* The proposition a) of Definition 14 is trivial from ii).

Let us consider a dart  $b$  which satisfies i) and an arbitrary dart  $d \in C$ . Using Lemma 3,  $d \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b)$  or  $d \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b\alpha_{i+1})$  with:

$$\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) \neq \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b\alpha_{i+1}).$$

Let us suppose that  $d \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b)$ . We have thus  $d = b\alpha_{j_1} \dots \alpha_{j_p}$  with  $j_k \in \{0, \dots, n\} - \{i, i+1\}$  for all  $k$ .

- If  $j_k \neq i+2$ , for any  $k \in \{1, \dots, p\}$  then  $\alpha_{i+1}$  commutes with any  $\alpha_{j_k}$ ,  $k \in \{1, \dots, p\}$  and we have:

$$d\alpha_{i+1} = b\alpha_{i+1}\alpha_{j_1} \dots \alpha_{j_p}.$$

- Otherwise, let us consider the greatest index  $h$  such that  $j_h = i+2$ . By definition of  $h$  we have:

$$\begin{aligned} d\alpha_{i+1} &= b\alpha_{j_1} \dots \alpha_{j_p}\alpha_{i+1} \\ &= b\alpha_{j_1} \dots \alpha_{j_{h-1}}\alpha_{i+2}\alpha_{i+1}\alpha_{j_{h+1}} \dots \alpha_{j_p} \end{aligned}$$

with both sequences  $\alpha_{j_1} \dots \alpha_{j_{h-1}}$  and  $\alpha_{j_{h+1}} \dots \alpha_{j_p}$  being possibly empty. Since  $b\alpha_{j_1} \dots \alpha_{j_{h-1}}$  belongs to  $\mathcal{C}$  we have by ii):

$$b\alpha_{j_1} \dots \alpha_{j_{h-1}}\alpha_{i+2}\alpha_{i+1}\alpha_{j_{h+1}} \dots \alpha_{j_p} = b\alpha_{j_1} \dots \alpha_{j_{h-1}}\alpha_{i+1}\alpha_{i+2}\alpha_{j_{h+1}} \dots \alpha_{j_p}$$

This process may be iterated on the sequence  $d\alpha_{j_1} \dots \alpha_{j_{h-1}}\alpha_{i+1}$  until  $\alpha_{i+1}$  reaches the dart  $b$ . We obtain thus finally:

$$d\alpha_{i+1} = b\alpha_{i+1}\alpha_{j_1} \dots \alpha_{j_p}$$

We have thus in both cases  $d\alpha_{i+1} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b\alpha_{i+1})$ . Since  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b\alpha_{i+1}) \neq \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b)$  and  $d \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b)$  by hypothesis we obtain:

$$d\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$$

The same demonstration may be conducted if  $d \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b\alpha_{i+1})$ .  $\square$

**Theorem 1** For any  $i \in \{0, \dots, n-2\}$ , an  $i$ -cell  $\mathcal{C}$  is a regular cell with local degree 2 if and only if

- i)  $\exists d \in \mathcal{C}$ ,  $d\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$ , and
- ii)  $\forall d \in \mathcal{C}$ ,  $d\alpha_{i+1}\alpha_{i+2} = d\alpha_{i+2}\alpha_{i+1}$

*Proof:* The reverse implication is provided by Lemma 3 (local degree 2) and 4 (regular). Let us show the implication. First, if  $\mathcal{C}$  is of local degree 2 it is not of local degree 1 and the property *i*) is provided by Property 3.

Secondly, let us consider a dart  $d \in \mathcal{C}$ . We have by condition *b*) of Definition 14 (and the fact that  $d\alpha_{i+2} \in \mathcal{C}$ ):

$$d\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d) \text{ and } d\alpha_{i+2}\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d)$$

Therefore if  $d\alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d\alpha_{i+2}\alpha_{i+1})$ , the three orbits  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d)$ ,  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d\alpha_{i+1})$  and  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d\alpha_{i+2}\alpha_{i+1})$  are distinct. However, in this case  $\mathcal{C}$  would be of local degree at least 3, which contradicts the hypothesis about the local degree 2 of  $\mathcal{C}$ . We have thus:

$$d\alpha_{i+1} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d\alpha_{i+2}\alpha_{i+1})$$

which implies that

$$d\alpha_{i+1}\alpha_{i+2} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle(d\alpha_{i+2}\alpha_{i+1})$$

Using property *a*) given by Definition 14, this last point implies that  $d\alpha_{i+1}\alpha_{i+2} = d\alpha_{i+2}\alpha_{i+1}$  which corresponds to *ii*).  $\square$

**Definition 15 (Local degree in maps)** *Let  $\mathcal{C}$  be an  $i$ -cell in an  $n$ -map.*

- *The local degree of  $\mathcal{C}$  is the number*

$$\begin{cases} \left| \{ \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle(b) \mid b \in \mathcal{C} \} \right| & \text{if } i \in \{0, \dots, n-2\} \\ \left| \{ \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-2} \rangle(b) \mid b \in \mathcal{C} \} \right| & \text{if } i = n-1 \end{cases}$$

- *The dual local degree of  $\mathcal{C}$  is the number*

$$\begin{cases} \left| \{ \langle \hat{\gamma}_i, \hat{\gamma}_{i-1} \rangle(b) \mid b \in \mathcal{C} \} \right| & \text{for } i \in \{1, \dots, n-1\} \\ \left| \{ \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-2} \rangle(b) \mid b \in \mathcal{C} \} \right| & \text{for } i = n \end{cases}$$

*The local degree (resp. dual local degree) of an  $n$ -cell (resp. a 0-cell) is 0.*

Let us justify the orbits considered in the definition of the local degree when  $i \in \{0, \dots, n-2\}$ . As for G-maps, we consider the darts that may be reached from  $d$  while allowing no change of  $i$ -cell (hence  $\hat{\gamma}_i$ ) and no change of  $(i+1)$ -cell (hence  $\hat{\gamma}_{i+1}$ ). In the case when  $i = n-1$ , preventing any change of  $(n-1)$ -cell means that the allowed involutions are in  $\{\gamma_0, \dots, \gamma_{n-2}\}$ , and preventing any change of  $n$ -cell means, according to Definition 10, that the set of allowed involutions is  $\{\gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-1}\}$ . Overall, only the involution  $\gamma_0\gamma_{n-1}$  of the

latter set is not allowed by the first one, therefore we obtain the orbit that must be considered, i.e.  $\langle \gamma_0 \gamma_1, \dots, \gamma_0 \gamma_{n-2} \rangle$ .

**Proposition 6** *Let  $G = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and let us consider  $d \in \mathcal{D}$ . The  $i$ -cell  $\mathcal{C}_i(d)$  is of local degree at most 2 if:*

- For  $i \in \{0, \dots, n-3\}$ ,  $b\gamma_{i+1}^{-1}\gamma_{i+2} = b\gamma_{i+2}^{-1}\gamma_{i+1}$  for all  $b \in \mathcal{C}_i(d)$ .
- For  $i = n-2$ ,  $b\gamma_{n-1}^{-1} = b\gamma_{n-1}$  for all  $b \in \mathcal{C}_i(d)$ .

Such a characterization may be equivalently performed in terms of the dual map  $\overline{G} = (\mathcal{D}, \beta_n, \dots, \beta_1)$ :

$$\forall i \in \{0, \dots, n-2\} \forall b \in \mathcal{C}_i(d), \quad b\beta_{i+1}^{-1}\beta_{i+2} = b\beta_{i+2}^{-1}\beta_{i+1}$$

*Proof:* Let us first show the equivalence between both characterizations:

- If  $i \in \{0, \dots, n-3\}$

$$\begin{aligned} d\gamma_{i+1}^{-1}\gamma_{i+2} &= d\beta_{i+1}^{-1}\beta_n^{-1}\beta_n\beta_{i+2} = d\beta_{i+1}^{-1}\beta_{i+2} \\ d\gamma_{i+2}^{-1}\gamma_{i+1} &= d\beta_{i+2}^{-1}\beta_n^{-1}\beta_n\beta_{i+1} = d\beta_{i+2}^{-1}\beta_{i+1} \end{aligned}$$

So that  $d\gamma_{i+1}^{-1}\gamma_{i+2} = d\gamma_{i+2}^{-1}\gamma_{i+1}$  if and only if  $d\beta_{i+1}^{-1}\beta_{i+2} = d\beta_{i+2}^{-1}\beta_{i+1}$ .

- If  $i = n-2$ :

$$d\gamma_{n-1} = d\beta_n\beta_{n-1} \text{ and } d\gamma_{n-1}^{-1} = d\beta_{n-1}^{-1}\beta_n^{-1}$$

Since  $\beta_n$  is an involution we obtain:

$$d\gamma_{n-1} = d\beta_n^{-1}\beta_{n-1} \text{ and } d\gamma_{n-1}^{-1} = d\beta_{n-1}^{-1}\beta_n$$

So that  $d\gamma_{n-1}^{-1} = d\gamma_{n-1}$  if and only if  $d\beta_{n-1}^{-1}\beta_n = d\beta_n^{-1}\beta_{n-1}$ .

Let us now show that the above equations characterize  $i$ -cells with local degree 2.

- If  $i \in \{0, \dots, n-3\}$  let us consider a dart  $d$  such that:

$$d\gamma_{i+1}^{-1}\gamma_{i+2} = d\gamma_{i+2}^{-1}\gamma_{i+1}$$

Since  $i \leq n-3$ ,  $\gamma_{i+1}$  is an involution and we have:

$$d\gamma_{i+1}^{-1}\gamma_{i+2} = d\gamma_{i+1}\gamma_{i+2} = d\gamma_{i+2}^{-1}\gamma_{i+1}$$

Since the above equation is valid for any dart  $d \in \mathcal{C}_i(d)$ , we may apply it to  $(d\gamma_{i+2})$  and we obtain:

$$(d\gamma_{i+2})\gamma_{i+2}^{-1}\gamma_{i+1} = d\gamma_{i+2}\gamma_{i+1}\gamma_{i+2} = d\gamma_{i+1}$$

We have thus:

$$d\gamma_{i+2}\gamma_{i+1} = d\gamma_{i+2}\gamma_{i+1}\gamma_{i+2}\gamma_{i+2}^{-1} = d\gamma_{i+1}\gamma_{i+2}^{-1}$$

Let us now consider one dart  $b \in \mathcal{C}_i(d) = \langle \gamma_0, \dots, \hat{\gamma}_i, \dots, \gamma_{n-1} \rangle (d)$ . The dart  $b$  is equal to  $d\varphi$  with  $\varphi \in \langle \gamma_0, \dots, \hat{\gamma}_i, \dots, \gamma_{n-1} \rangle$ . Let us consider  $\varphi$  as a word built on the alphabet  $\{\gamma_0, \dots, \hat{\gamma}_i, \dots, \gamma_{n-1}\} \cup \{\gamma_0^{-1}, \dots, \hat{\gamma}_i^{-1}, \dots, \gamma_{n-1}^{-1}\}$ . Within the general case, the symbol  $\gamma_{i+1}$  commutes with all the symbols of this alphabet except  $\gamma_{i+2}$  and  $\gamma_{i+2}^{-1}$ . But as we have shown, the relationship  $d\gamma_{i+1}^{-1}\gamma_{i+2} = d\gamma_{i+2}^{-1}\gamma_{i+1}$  induces for all  $d \in \mathcal{C}$ :

$$\begin{cases} d\gamma_{i+2}\gamma_{i+1} = d\gamma_{i+1}\gamma_{i+2}^{-1} \\ d\gamma_{i+2}^{-1}\gamma_{i+1} = d\gamma_{i+1}\gamma_{i+2} \end{cases}$$

We may thus consider the natural  $p$  and the function

$$\psi \in \langle \gamma_0, \dots, \hat{\gamma}_i, \gamma_{i+1}, \dots, \gamma_{n-1} \rangle (d)$$

such that  $b = d\gamma_{i+1}^p\psi$ .

Since  $i \leq n - 3$ ,  $\gamma_{i+1}$  is an involution and:

– If  $p$  is even  $d\gamma_{i+1}^p = d$  and:

$$b = d\psi \in \langle \gamma_0, \dots, \gamma_{i+1}, \dots, \gamma_{n-1} \rangle (d) = \mathcal{C}_{i+1}(d)$$

– If  $p$  is odd  $d\gamma_{i+1}^p = d\gamma_{i+1}$  and:

$$b = d\gamma_{i+1}\psi \in \langle \gamma_0, \dots, \gamma_{i+1}, \dots, \gamma_{n-1} \rangle (d) = \mathcal{C}_{i+1}(d\gamma_{i+1})$$

Therefore any dart of  $\mathcal{C}_i(d)$  belongs either to  $\mathcal{C}_{i+1}(d)$  or to  $\mathcal{C}_{i+1}(d\gamma_{i+1})$ ,  $\mathcal{C}_i(d)$  is thus incident to at most two  $i + 1$  cells and its degree is at most 2.

- If  $i = n - 2$ ,  $\mathcal{C}_{n-2}(d) = \langle \gamma_0, \dots, \gamma_{n-3}, \gamma_{n-1} \rangle (d)$ . The permutation  $\gamma_{n-1}$  commutes with all  $\gamma_i$ ,  $i \leq n - 3$  and we have thus as previously, for each  $b \in \mathcal{C}_0(d)$  a function  $\varphi \in \langle \gamma_0, \dots, \gamma_{n-3} \rangle$  such that  $b = d\gamma_{n-1}^p\varphi$ . We have thus  $b \in \mathcal{C}_{n-1}(d)$  if  $p$  is even and  $b \in \mathcal{C}_{n-1}(d\gamma_{n-1})$  if  $p$  is odd. The  $n - 2$  cell  $\mathcal{C}_{n-2}(d)$  is thus incident to at most two  $n - 1$  cells: Its degree is at most 2.

□

**Definition 16 (Regular cell in  $n$ -maps)** *A cell in an  $n$ -map is said to be regular if it satisfies the two conditions a) and b) below:*

a) *If  $i < n - 3$ , for all  $d \in \mathcal{C}$  we have:*

$$d\gamma_{i+1}\gamma_{i+2} = d\gamma_{i+2}\gamma_{i+1} \text{ or } d\gamma_{i+1}\gamma_{i+2} \notin \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\gamma_{i+2}\gamma_{i+1})$$

If  $i = n - 3$ , for all  $d \in \mathcal{C}$  we have:

$$d\gamma_{n-2}\gamma_{n-1} = d\gamma_{n-1}^{-1}\gamma_{n-2} \text{ and } d\gamma_{n-2}\gamma_{n-1}^{-1} = d\gamma_{n-1}\gamma_{n-2}, \text{ or}$$

$$d\gamma_{n-2} \notin \left( \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})\gamma_{n-1}^{-1} \cup \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}\gamma_{n-2})\gamma_{n-1} \right)$$

If  $i = n - 2$ , for all  $d \in \mathcal{C}$  we have:

$$d\gamma_{n-1}^{-1} = d\gamma_{n-1}, \text{ or } d\gamma_{n-1}^{-1} \notin \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d\gamma_{n-1})$$

b) If  $i < n - 2$ , for all  $b \in \mathcal{C}$  we have:

$$b\gamma_{i+1} \notin \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b)$$

If  $i = n - 2$ , for all  $b \in \mathcal{C}$  we have:

$$\{b\gamma_{n-1}, b\gamma_{n-1}^{-1}\} \cap \langle \gamma_0, \dots, \gamma_{n-3} \rangle (b) = \emptyset$$

**Remark 4** If  $\gamma$  is a permutation of a set  $S$ , then for all  $s \in S$  there exists  $p \in \mathbb{N}$  such that

$$s\gamma = \overbrace{s\gamma^{-1} \dots \gamma^{-1}}^p = s\gamma^{-p}$$

Conversly, for all  $s \in S$  there exists  $q \in \mathbb{N}$  such that  $s\gamma^{-1} = s\gamma^q$ .

**Notation 2** If  $\mathcal{D}$  and  $\mathcal{D}'$  are sets,  $\sigma : \mathcal{D} \rightarrow \mathcal{D}'$ , and  $S \subset \mathcal{D}$ , we denote by  $S\sigma$  the image of  $S$  by  $\sigma$ , i.e.

$$S\sigma = \{s\sigma \mid s \in S\}$$

**Proposition 7** Let  $M$  be an  $n$ -map and  $\tilde{G} = AG(M)$ . If  $\mathcal{C}$  is an  $i$ -cell of  $M$ , then the set  $\tilde{\mathcal{C}} = \mathcal{C} \cup \mathcal{C}\sigma$  is an  $i$ -cell of  $\tilde{G}$  if  $i < n$ , and  $\tilde{\mathcal{C}} = \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$  is an  $n$ -cell of  $\tilde{G}$  if  $i = n$ .

**Corollary 2** With the notations of Proposition 7 we have:

$$\forall d \in \mathcal{C}, \langle \hat{\alpha}_i \rangle (d) = \tilde{\mathcal{C}}$$

*Proof of Proposition 7:*

• If  $i < n$ . We prove that for all  $b \in \mathcal{C} \cup \mathcal{C}\sigma$ ,  $\langle \hat{\alpha}_i \rangle (b) = \mathcal{C} \cup \mathcal{C}\sigma = \mathcal{C} \cup \mathcal{C}\alpha_n$ . Let us show first that  $\langle \hat{\alpha}_i \rangle (b) \subset \mathcal{C} \cup \mathcal{C}\sigma$ . Let  $d \in \langle \hat{\alpha}_i \rangle (b)$ , we have  $d = b\alpha_{k_1}\alpha_{k_2} \dots \alpha_{k_p}$  where  $p \in \mathbb{N}$  and  $k_h \in \{0, \dots, n\} \setminus \{i\}$ ,  $0 \leq h \leq p$ . (Note that  $\alpha_i = \alpha_i^{-1}$  for all  $i \in \{0, \dots, n\}$ , hence there is no need to consider inverse involutions in the sequence  $\alpha_{k_1} \dots \alpha_{k_p}$ .)



We prove by recurrence on  $p$ , the length of the sequence  $\alpha_{k_1}\alpha_{k_2}\dots\alpha_{k_p}$ , that  $d \in \mathcal{C} \cup \mathcal{C}\sigma$ . First, if  $p = 0$  we have  $d = b \in \mathcal{C} \cup \mathcal{C}\sigma$  and there is nothing left to prove. Thus, the property holds for  $p = 0$ .

Now we suppose that the property is satisfied for  $p \in \mathbb{N}^*$  and we consider a dart  $d = b\alpha_{k_1}\dots\alpha_{k_p}\alpha_{k_{p+1}}$ . We denote  $b' = b\alpha_{k_1}\dots\alpha_{k_p}$ . Since the property is valid for  $p$ , we have  $b' \in \mathcal{C}$  or  $b' \in \mathcal{C}\sigma$ .

If  $b' \in \mathcal{C}$ , we deduce from Definition 7 that

$$b'\alpha_{k_{p+1}} = \begin{cases} b'\gamma_{k_{p+1}}\sigma & \text{if } k_{p+1} < n-1 \\ b'\gamma_{n-1}^{-1}\sigma & \text{if } k_{p+1} = n-1 \\ b'\sigma & \text{if } k_{p+1} = n \end{cases}$$

so that in all cases  $b'\alpha_{k_{p+1}} \in \langle \hat{\gamma}_i \rangle (d)\sigma = \mathcal{C}\sigma$ .

If  $b' \in \mathcal{C}\sigma$  we have  $b' = b''\sigma$  with  $b'' \in \mathcal{C}$ . Again, following Definition 7 and the fact that  $\mathcal{C}\sigma \subset \mathcal{D}'$ , we have

$$d = b'\alpha_{k_{p+1}} = b''\sigma\alpha_{k_{p+1}} = \begin{cases} b''\sigma\sigma^{-1}\gamma_{k_{p+1}} = b''\gamma_{k_{p+1}} & \text{if } k_{p+1} < n \\ b''\sigma\sigma^{-1} = b'' & \text{if } k_{p+1} = n \end{cases}$$

so that  $b'\alpha_{k_{p+1}} \in \mathcal{C}$  since  $b'' \in \mathcal{C}$  and  $k_{p+1} \neq i$ .

From the two latter cases, we obtain that  $b\alpha_{k_1}\dots\alpha_{k_p}\alpha_{k_{p+1}} \in \mathcal{C} \cup \mathcal{C}\sigma$ ; hence the property is valid for all  $p \in \mathbb{N}^*$ . We conclude that  $\langle \hat{\alpha}_i \rangle (b) \subset \mathcal{C} \cup \mathcal{C}\sigma$ .

We prove now that  $\langle \hat{\alpha}_i \rangle (b) \supset \mathcal{C} \cup \mathcal{C}\sigma$ . Since  $\mathcal{C} = \langle \hat{\gamma}_i \rangle (b)$ , we deduce from Lemma 1 that the orbit

$$\langle \gamma_1, \dots, \hat{\gamma}_i, \dots, \gamma_{n-1} \rangle (b) \text{ in } M$$

is precisely

$$\langle \alpha_n\alpha_0, \dots, \alpha_n\hat{\alpha}_i, \dots, \alpha_n\alpha_{n-1} \rangle (b) \text{ in } AG(M).$$

Since  $i < n$  we have

$$\langle \alpha_n\alpha_0, \dots, \alpha_n\hat{\alpha}_i, \dots, \alpha_n\alpha_{n-1} \rangle (b) \subset \langle \alpha_0, \dots, \hat{\alpha}_i, \dots, \alpha_n \rangle (b)$$

Eventually,  $\mathcal{C} \subset \langle \hat{\alpha}_i \rangle (b)$ . Since  $i \neq n$ , we immediatly obtain that  $\mathcal{C}\sigma = \mathcal{C}\alpha_n \subset \langle \hat{\alpha}_i \rangle (b)$ .

We conclude that  $\langle \hat{\alpha}_i \rangle (b) = \mathcal{C} \cup \mathcal{C}\sigma$ .

• If  $i = n$ . Let  $b \in \mathcal{C}$ , we prove that  $\langle \hat{\alpha}_n \rangle (b) = \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$  where

$$\mathcal{C} = \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-1} \rangle (b)$$

– ( $\langle \hat{\alpha}_n \rangle (b) \subset \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$ ) Let  $d \in \langle \hat{\alpha}_n \rangle (b)$ . We have  $d = b\alpha_{k_1} \dots \alpha_{k_p}$  for  $p \in \mathbb{N}$ , with  $k_h \in \{0, \dots, n-1\}$  for  $1 \leq h \leq p$ .

We prove by recurrence on  $p$ , the length of the sequence  $\alpha_{k_1} \dots \alpha_{k_p}$ , that  $d \in \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$ . If  $p = 0$ , we have  $d = b \in \mathcal{C}$  and there is nothing left to prove.

Thus, we suppose that the property holds for some  $p \in \mathbb{N}$  and we consider a dart  $d = b\alpha_{k_1} \dots \alpha_{k_p} \alpha_{k_{p+1}}$ . We denote  $d' = b\alpha_{k_1} \dots \alpha_{k_p}$ , so from the recurrence hypothesis we have  $d' \in \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$ .

If  $d' \in \mathcal{C}$ , from Definition 7 we obtain that:

- If  $k_{p+1} = 0$ ,  $d'\alpha_{k_{p+1}} = d'\alpha_0\alpha_n\alpha_n = d'\alpha_n\alpha_0\alpha_n = d'(\gamma_0\sigma) \in \mathcal{C}\gamma_0\sigma$ .
- If  $0 < k_{p+1} \leq n-1$ ,

$$\begin{aligned} d'\alpha_{k_{p+1}} &= d'\alpha_{k_{p+1}}\sigma^{-1}\gamma_0\gamma_0\sigma \\ &= d'\alpha_{k_{p+1}}\alpha_n\gamma_0\gamma_0\sigma \\ &= d'(\alpha_n\alpha_{k_{p+1}})^{-1}\gamma_0\gamma_0\sigma \\ &= d'\gamma_{k_{p+1}}^{-1}\gamma_0\gamma_0\sigma \quad (\text{By Lemma 1}) \\ &= d'(\gamma_0\gamma_{k_{p+1}})^{-1}\gamma_0\sigma \end{aligned}$$

Since  $d' \in \mathcal{C}$  we have  $d'(\gamma_0\gamma_{k_{p+1}})^{-1} \in \mathcal{C}$ , hence  $d'\alpha_{k_{p+1}} \in \mathcal{C}\gamma_0\sigma$ .

If  $d' \in \mathcal{C}\gamma_0\sigma$  then  $d' = d''\gamma_0\sigma$  for some dart  $d'' \in \mathcal{C}$  and we have

$$\begin{aligned} d'\alpha_{k_{p+1}} &= d''\gamma_0\sigma\alpha_{k_{p+1}} \\ &= d''\gamma_0\sigma\sigma^{-1}\gamma_{k_{p+1}} \quad (\text{since } d''\gamma_0\sigma \in \mathcal{D}' \text{ and } k_{p+1} < n) \\ &= d''\gamma_0\gamma_{k_{p+1}} \end{aligned}$$

Since  $d'' \in \mathcal{C}$ , we obtain that  $d'\alpha_{k_{p+1}} \in \mathcal{C} = \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-1} \rangle (b)$ .

Eventually, either  $d \in \mathcal{C}\gamma_0\sigma$  or  $d \in \mathcal{C}$ , i.e.  $d \in \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$ , and the property holds for  $p+1$ .

– ( $\mathcal{C} \cup \mathcal{C}\gamma_0\sigma \subset \langle \hat{\alpha}_n \rangle (b)$ ) We have  $\mathcal{C} = \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-1} \rangle (b)$ . From Lemma 1 we deduce that the orbit  $\langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-1} \rangle (b)$  in  $M$  is precisely

$$\langle \alpha_n\alpha_0\alpha_n\alpha_1, \dots, \alpha_n\alpha_0\alpha_n\alpha_{n-1} \rangle (b) \text{ in } AG(M)$$

and since  $n \geq 2$  we have

$$\begin{aligned} \langle \alpha_n\alpha_0\alpha_n\alpha_1, \dots, \alpha_n\alpha_0\alpha_n\alpha_{n-1} \rangle (b) &= \langle \alpha_0\alpha_n\alpha_n\alpha_1, \dots, \alpha_0\alpha_n\alpha_n\alpha_{n-1} \rangle (b) \\ &= \langle \alpha_0\alpha_1, \dots, \alpha_0\alpha_{n-1} \rangle (b) \end{aligned}$$

We observe that  $\langle \alpha_0 \alpha_1, \dots, \alpha_0 \alpha_{n-1} \rangle (b) \subset \langle \hat{\alpha}_n \rangle (b)$ , hence  $\mathcal{C} \subset \langle \hat{\alpha}_n \rangle (b)$ . On the other hand, for all dart  $d \in \mathcal{C}$ ,  $d\gamma_0\sigma = d\alpha_n\alpha_0\alpha_n$ . Since  $n \geq 2$  we obtain  $d\gamma_0\sigma = d\alpha_0\alpha_n\alpha_n = d\alpha_0$ . From  $\mathcal{C} \subset \langle \hat{\alpha}_n \rangle (b)$  and  $d \in \mathcal{C}$  we deduce that  $d \in \langle \hat{\alpha}_n \rangle (b)$ , thus  $d\alpha_0 \in \langle \hat{\alpha}_n \rangle (b)$ . Eventually,  $d\gamma_0\sigma \in \langle \hat{\alpha}_n \rangle (b)$  so that  $\mathcal{C}\gamma_0\sigma \subset \langle \hat{\alpha}_n \rangle (b)$ .

We conclude that  $\langle \hat{\alpha}_n \rangle (b) = \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$ .  $\square$

**Definition 17 (Associated cell)** *The cell  $\tilde{\mathcal{C}}$  as defined in Proposition 7 will be called the associated cell of  $\mathcal{C}$  in  $AG(M)$ .*

Now, we will prove that if a cell of a map  $M$  has a local degree of 2, then its associated cell in  $AG(M)$  also has a local degree of 2. This result will be stated by Proposition 8.

**Lemma 5** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and  $AG(M) = (\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}', \alpha_0, \dots, \alpha_n)$  be the associated  $n$ -G-map of  $M$ . Let  $\mathcal{C}$  be an  $i$ -cell with local degree 2 in  $M$ , for  $0 \leq i < n$ , and  $C_1, C_2$  be the two sets of darts defined (following Definition 15) by*

- $\{C_1, C_2\} = \{ \langle \hat{\gamma}_i, \gamma_{i+1} \rangle (b) \mid b \in \mathcal{C} \}$  if  $i < n$ , and
- $\{C_1, C_2\} = \{ \langle \gamma_0 \gamma_1, \dots, \gamma_0 \gamma_{n-2} \rangle (b) \mid b \in \mathcal{C} \}$  if  $i = n - 1$ .

Then we have

$$(C_1 \cup C_1\gamma_0\alpha_n) \cap (C_2 \cup C_2\gamma_0\alpha_n) = \emptyset$$

*Proof:*

– If  $i < n - 1$ , we first rewrite

$$\begin{aligned} (C_1 \cup C_1\alpha_n) \cap (C_2 \cup C_2\alpha_n) &= ((C_1 \cup C_1\alpha_n) \cap C_2) \cup ((C_1 \cup C_1\alpha_n) \cap C_2\alpha_n) \\ &= ((C_1 \cap C_2) \cup (C_1\alpha_n \cap C_2)) \cup ((C_1 \cap C_2\alpha_n) \cup (C_1\alpha_n \cap C_2\alpha_n)) \end{aligned}$$

From  $C_1 \cap C_2 = \emptyset$  and the fact that  $\alpha_n$  is a one-to-one map from  $\mathcal{D}$  to  $\mathcal{D}'$  we deduce that  $C_1\alpha_n \cap C_2\alpha_n = \emptyset$ . Since  $\mathcal{D} \cap \mathcal{D}' = \emptyset$  and  $\alpha_n$  is a map from  $\mathcal{D}$  to  $\mathcal{D}'$  we also have  $C_1 \cap C_1\alpha_n = \emptyset$ ,  $C_1 \cap C_2\alpha_n = \emptyset$ ,  $C_2 \cap C_2\alpha_n = \emptyset$ , and  $C_1 \cap C_2\alpha_n = \emptyset$ . Thus, all the intersections of the above union of sets are empty.

– If  $i = n - 1$ , we rewrite

$$\begin{aligned}
(C_1 \cup C_1\gamma_0\alpha_n) \cap (C_2 \cup C_2\gamma_0\alpha_n) &= ((C_1 \cup C_1\gamma_0\alpha_n) \cap C_2) \\
&\quad \cup ((C_1 \cup C_1\gamma_0\alpha_n) \cap C_2\gamma_0\alpha_n) \\
&= (C_1 \cap C_2) \cup (C_1\gamma_0\alpha_n \cap C_2) \\
&\quad \cup (C_1 \cap C_2\gamma_0\alpha_n) \cup (C_1\gamma_0\alpha_n \cap C_2\gamma_0\alpha_n)
\end{aligned}$$

From  $C_1 \cap C_2 = \emptyset$  and the fact that  $\gamma_0\alpha_n$  is a one-to-one map from  $\mathcal{D}$  to  $\mathcal{D}'$  we deduce that  $C_1\gamma_0\alpha_n \cap C_2\gamma_0\alpha_n = \emptyset$ . Since  $\mathcal{D} \cap \mathcal{D}' = \emptyset$  and  $\gamma_0\alpha_n$  is a map from  $\mathcal{D}$  to  $\mathcal{D}'$  we also have  $C_1 \cap C_1\gamma_0\alpha_n = \emptyset$ ,  $C_1 \cap C_2\gamma_0\alpha_n = \emptyset$ ,  $C_2 \cap C_2\gamma_0\sigma = \emptyset$ , and  $C_1 \cap C_2\gamma_0\alpha_n = \emptyset$ . Thus, all the intersections of the above union of sets are empty.  $\square$

**Lemma 6** *If  $\mathcal{C}$  is an  $(n - 1)$ -cell with local degree 2 in an  $n$ -map  $M$ , then the associated cell of  $\mathcal{C}$  in  $AG(M)$  has a local degree 2.*

*Proof:* Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$ ,  $AG(M) = (\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}', \alpha_0, \dots, \alpha_n)$  following Definition 7.

If  $\mathcal{C}$  has local degree 2 in  $M$  we have:

$$\{ \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-2} \rangle (b) \mid b \in \mathcal{C} \} = \{C_1, C_2\}$$

where  $C_1$  and  $C_2$  are non-empty and disjoint sets. Thus, there exist  $b_1, b_2 \in \mathcal{C}$  such that

- $C_1 = \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-2} \rangle (b_1)$ ,
- $C_2 = \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-2} \rangle (b_2)$ ,
- $\forall d \in \mathcal{C}, \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-2} \rangle (d) \in \{C_1, C_2\}$ .

Now, with  $\tilde{\mathcal{C}} = \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$ , we prove that

$$\left| \{ \langle \alpha_{n-1}, \hat{\alpha}_n \rangle (d) \mid d \in \tilde{\mathcal{C}} \} \right| = \{C_1 \cup C_1\gamma_0\sigma, C_2 \cup C_2\gamma_0\sigma\}$$

Let  $d \in \tilde{\mathcal{C}}$ . We may suppose without loss of generality that  $d \in C_1$  if  $d \in \mathcal{C}$  and that  $d\sigma\gamma_0 \in C_1$  if  $d \in \mathcal{C}\gamma_0\sigma$ . In all cases, we prove that  $\langle \hat{\alpha}_{n-1}, \hat{\alpha}_n \rangle (d) = C_1 \cup C_1\gamma_0\sigma$ .

Thus, let  $d \in \mathcal{C} \cup \mathcal{C}\gamma_0\sigma$ , we consider the set  $\langle \hat{\alpha}_{n-1}, \hat{\alpha}_n \rangle (d)$ . If  $d'$  is a dart of the latter orbit, we have

$$d' = d\alpha_{k_1} \dots \alpha_{k_p}, p \in \mathbb{N}$$

where  $k_j \in \{0, \dots, n - 2\}$ ,  $1 \leq j \leq p$ .

We prove by recurrence on  $p$ , the length of the sequence  $\alpha_{k_1} \dots \alpha_{k_p}$ , that  $d' \in C_1 \cup C_1\gamma_0\sigma$  with

$$C_1 = \langle \gamma_0\gamma_1, \dots, \gamma_0\gamma_{n-2} \rangle (d) \quad (2)$$

The case  $p = 0$  comes from the assumption we made on  $d$  or  $d\sigma\gamma_0$ . Therefore, we suppose that the property holds for some  $p \in \mathbb{N}$ .

We have  $d' = d\alpha_{k_1} \dots \alpha_{k_p} \alpha_{k_{p+1}}$  with  $k_j \in \{0, \dots, n-2\}$ ,  $1 \leq j \leq p+1$ . Let us denote  $b = d\alpha_{k_1} \dots \alpha_{k_p}$ . From the recurrence hypothesis we know that  $b \in C_1 \cup C_1\gamma_0\sigma$ .

If  $b \in C_1$ , from Definition 7 and the fact that  $k_{p+1} \leq n-2$  we have

$$d' = b\alpha_{k_{p+1}} = d\gamma_{k_{p+1}}\sigma$$

We may rewrite

$$d' = \begin{cases} b\gamma_0\sigma & \text{if } k_{p+1} = 0 \\ b\gamma_{k_{p+1}}\sigma(\sigma^{-1}\gamma_0\gamma_0\sigma) = d(\gamma_{k_{p+1}}\gamma_0)\gamma_0\sigma & \text{if } 0 < k_{p+1} < n-1 \end{cases}$$

In the second case,  $\gamma_{k_{p+1}}$  is an involution since  $k_{p+1} < n-1$  therefore  $d(\gamma_{k_{p+1}}\gamma_0) = d(\gamma_0\gamma_{k_{p+1}})^{-1}$ . Thus, in both cases  $b \in C_1$  implies that  $d' \in C_1\gamma_0\sigma$  (see 2).

If  $b \in C_1\gamma_0\sigma$ , then  $b = b'\gamma_0\sigma$  for some dart  $b' \in C_1$ . Then again from Definition 7 we have  $d' = b\sigma^{-1}\gamma_{k_{p+1}} = b''\gamma_0\sigma\sigma^{-1}\gamma_{k_{p+1}} = b''\gamma_0\gamma_{k_{p+1}}$ . If  $k_{p+1} = 0$  we obtain that  $d' = b''\gamma_0\gamma_0 = b'' \in C_1$ , otherwise  $d' = b''\gamma_0\gamma_{k_{p+1}} \in C_1$  by (2).

We conclude that  $b\alpha_{k_{p+1}} \in C_1 \cup C_1\gamma_0\sigma$ , so that the property holds for  $p+1$ , hence for all  $p \in \mathbb{N}$ . Eventually,  $\langle \alpha_{\hat{n}-1}, \hat{\alpha}_n \rangle (d) \subset C_1 \cup C_1\gamma_0\sigma$ .

Now, from the definition of  $C_1$  (2) it is straightforward that  $C_1 \subset \langle \alpha_0, \dots, \alpha_{n-2} \rangle (d)$ . On the other hand, we have  $C_1\gamma_0\sigma = C_1\alpha_n\alpha_0\alpha_n$ . Since  $n \geq 2$  we obtain  $C_1\gamma_0\sigma = C_1\alpha_0$ . Therefore,  $C_1 \subset \langle \alpha_0, \dots, \alpha_{n-2} \rangle (d)$  implies that  $C_1\gamma_0\sigma \subset \langle \alpha_0, \dots, \alpha_{n-2} \rangle (d)$ . Thus we have  $C_1 \cup C_1\gamma_0\sigma \subset \langle \alpha_0, \dots, \alpha_{n-2} \rangle (d)$ .

Finally, for all dart  $d \in \tilde{\mathcal{C}}$ , we have proved that  $\langle \alpha_0, \dots, \alpha_{n-2} \rangle (d) = C_1 \cup C_1\gamma_0\sigma$  or  $\langle \alpha_0, \dots, \alpha_{n-2} \rangle (d) = C_2 \cup C_2\gamma_0\sigma$ . Since  $C_1 \cup C_1\gamma_0\sigma$  and  $C_2 \cup C_2\gamma_0\sigma$  are distinct sets (Lemma 5), we obtain that  $\tilde{\mathcal{C}}$  has a local degree 2 according to Definition 12.  $\square$

**Lemma 7** *If  $\mathcal{C}$  is an  $i$ -cell with local degree 2 in an  $n$ -map  $M$  for  $i < n-1$ , then the associated cell of  $\mathcal{C}$  in  $AG(M)$  has local degree 2.*

*Proof:* Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  and  $AG(M) = (\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}', \alpha_0, \dots, \alpha_n)$  following Definition 7.

Since  $i < n - 1$  and  $\mathcal{C}$  has local degree 2 in  $M$  we have:

$$\left\{ \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b) \mid b \in \mathcal{C} \right\} = \{C_1, C_2\}$$

where  $C_1$  and  $C_2$  are non-empty disjoint sets. Thus, there exists  $b_1, b_2 \in \mathcal{C}$  such that

- $C_1 = \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b_1)$ ,
- $C_2 = \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b_2)$ ,
- $\forall d \in \mathcal{D}, \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d) \in \{C_1, C_2\}$ .

With  $\tilde{\mathcal{C}} = \mathcal{C} \cup \mathcal{C}\sigma$ , we prove that

$$\left\{ \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d) \mid d \in \tilde{\mathcal{C}} \right\} = \{C_1 \cup C_1\sigma, C_2 \cup C_2\sigma\}$$

Let  $d \in \tilde{\mathcal{C}}$ . We may suppose without loss of generality that  $d \in C_1$  if  $d \in \mathcal{C}$  and that  $d\sigma^{-1} \in C_1$  if  $d \in \mathcal{C}\sigma$ . In all cases, we prove that  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d) = C_1 \cup C_1\sigma$ .

Thus, let  $d \in \tilde{\mathcal{C}}$ , we consider the set  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$ . Let  $d'$  be a dart of the latter orbit. We have:

$$d' = d\alpha_{k_1}\alpha_{k_2}\dots\alpha_{k_q}, \quad q \in \mathbb{N}$$

where  $k_j \in \{0, \dots, n\} \setminus \{i, i+1\}$  for  $j \in \{1, \dots, q\}$ .

We prove by recurrence on  $p$ , the length of the sequence  $\alpha_{k_1}\alpha_{k_2}\dots\alpha_{k_p}$ , that  $d' \in C_1 \cup C_1\sigma$  with  $C_1 = \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b_1)$ . If  $p = 0$ , since we supposed that  $d \in C_1$  or  $d\sigma^{-1} \in C_1$  (i.e.  $d \in C_1\sigma$ ) the property holds and there is nothing left to prove.

Now, we suppose that the property is verified for some  $p \in \mathbb{N}$ . Let  $d' = d\alpha_{k_1}\alpha_{k_2}\dots\alpha_{k_p}\alpha_{k_{p+1}}$  with  $d'' = d\alpha_{k_1}\alpha_{k_2}\dots\alpha_{k_p}$ . From the recurrence hypothesis we have  $d'' \in C_1 \cup C_1\sigma$ . If  $d'' \in C_1$ , by Definition 7 we obtain that  $d' = d''\gamma_{k_{p+1}}\sigma$  (if  $k_{p+1} < n - 1$ ),  $d' = d''\gamma_{n-1}^{-1}\sigma$  (if  $k_{p+1} = n - 1$ ), or  $d' = d''\sigma$  (if  $k_{p+1} = n$ ); therefore in all cases  $d' \in C_1\sigma$ . If  $d'' \in C_1\sigma$ , we have  $d' = d''\sigma^{-1}\gamma_{k_{p+1}}$  (if  $k_{p+1} < n$ ) or  $d' = d''\sigma^{-1}$  (if  $k_{p+1} = n$ ); so that in both cases  $d' \in C_1$ . We conclude that  $d' = d\alpha_{k_1} \in C_1 \cup C_1\sigma$  and the property holds for  $p + 1$ , hence for any  $p \in \mathbb{N}$ .

Eventually, we obtained that

$$\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d) \subset C_1 \cup C_1\sigma$$

Now, we show that  $C_1 \cup C_1\sigma \subset \langle \hat{\alpha}_i, \alpha_{i+1} \rangle (d)$ . We have  $C_1 = \langle \hat{\gamma}_i, \gamma_{i+1} \rangle (b_1) = \langle \hat{\gamma}_i, \gamma_{i+1} \rangle (d)$  and by Lemma 1:

$$\langle \hat{\gamma}_i, \gamma_{i+1} \rangle (d) = \langle \alpha_n \alpha_0, \dots, \alpha_n \hat{\alpha}_i, \alpha_n \hat{\alpha}_{i+1}, \dots, \alpha_n \alpha_{n-1} \rangle (d)$$

Since  $i < n - 1$ , we have  $\alpha_n \in \{\alpha_0, \dots, \alpha_n\} \setminus \{\alpha_i, \alpha_{i+1}\}$ , therefore

$$\langle \alpha_n \alpha_0, \dots, \alpha_n \hat{\alpha}_i, \alpha_n \hat{\alpha}_{i+1}, \dots, \alpha_n \alpha_{n-1} \rangle (d) \subset \langle \hat{\alpha}_i, \alpha_{i+1} \rangle (d)$$

Finally,  $C_1 \subset \langle \hat{\alpha}_i, \alpha_{i+1} \rangle (d)$ . Since  $i + 1 < n$ , this also implies that  $C_1 \alpha_n = C_1 \sigma \subset \langle \hat{\alpha}_i, \alpha_{i+1} \rangle (d)$ .

We conclude that  $\langle \hat{\alpha}_i, \alpha_{i+1} \rangle (d) = C_1 \cup C_1\sigma$ .

The overall result is that for all  $d \in \tilde{\mathcal{C}}$ , either

- i)  $\langle \hat{\alpha}_i, \alpha_{i+1} \rangle (d) = C_1 \cup C_1\sigma$ , or
- ii)  $\langle \hat{\alpha}_i, \alpha_{i+1} \rangle (d) = C_2 \cup C_2\sigma$ .

where  $C_1 \cup C_1\sigma$  and  $C_2 \cup C_2\sigma$  are disjoint sets (by Lemma 5). In other words:

$$\left| \left\{ \langle \hat{\alpha}_i, \alpha_{i+1} \rangle (d) \mid d \in \tilde{\mathcal{C}} \right\} \right| = 2$$

or again,  $\tilde{\mathcal{C}}$  has a local degree 2 according to Definition 12.  $\square$

**Proposition 8** *If  $M$  is an  $n$ -map and  $\mathcal{C}$  is an  $i$ -cell with local degree 2 in  $M$  (Definition 15) for  $0 \leq i \leq n - 1$ , then the associated cell of  $\mathcal{C}$  in  $AG(M)$  has a local degree of 2 (Definition 12).*

*Proof:* The case  $i = n - 1$  is proved by Lemma 6, and the case  $i < n - 1$  by Lemma 7.  $\square$

**Lemma 8** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and  $AG(M) = (\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}', \alpha_0, \dots, \alpha_n)$  be an associated  $n$ -G-map of  $M$  following Definition 7. Let  $\Psi = \{\gamma_{k_1}, \dots, \gamma_{k_p}\} \subset \{\gamma_0, \dots, \gamma_{n-1}\}$  for  $p \leq n$ , and  $\Phi = \{\alpha_{k_1}, \dots, \alpha_{k_p}\}$ . For all  $b \in \mathcal{D}$  we have*

$$\langle \Phi \rangle (b) \subset \left( \langle \Psi \rangle (b) \cup \langle \Psi \rangle (b) \alpha_n \right)$$

**Corollary 3** *With the notations of Lemma 8, for all  $i \leq n - 2$  and all  $b \in \mathcal{D}$  we have:*

$$\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) \subset \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b) \cup \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b) \alpha_n$$

*Proof of Lemma 8:* Let  $d \in \langle \Phi \rangle (b)$ . We may write

$$d = b \alpha_{h_1} \dots \alpha_{h_q}, \quad q \in \mathbb{N}$$

where  $h_j \in \{k_1, \dots, k_p\}$  for all  $j \in \{1, \dots, q\}$ .

We prove by recurrence on  $q$ , the length of the sequence of involutions  $\alpha_{h_1} \dots \alpha_{h_q}$ , that either  $d \in \langle \Psi \rangle (b)$  or  $d \in \langle \Psi \rangle (b)\alpha_n$ . The property is immediately verified for  $q = 0$ . Thus we assume that the property is valid for some integer  $p$  and we consider the dart  $d$  with

$$d = b\alpha_{h_1} \dots \alpha_{h_q}\alpha_{h_{q+1}}, \quad q \in \mathbb{N} \text{ and } h_j \in \{k_1, \dots, k_p\} \text{ for } 1 \leq j \leq q + 1$$

By the recurrence hypothesis, we have  $d = b'\alpha_{h_{q+1}}$  where  $b' \in \langle \Psi \rangle (b) \cup \langle \Psi \rangle (b)\alpha_n$ .

If  $b' \in \langle \Psi \rangle (b)$  we write  $d = b'\alpha_{h_{q+1}}\alpha_n\alpha_n = b'(\alpha_n\alpha_{h_{q+1}})^{-1}\alpha_n = b'(\gamma_{h_{q+1}})^{-1}\alpha_n$ , if  $h_{q+1} \neq n$ , and we obtain that  $d \in \langle \Psi \rangle (b)\alpha_n$ . The same result is immediately obtained when  $h_{q+1} = n$  since in this case  $d = b'\alpha_n$ .

If  $b' \in \langle \Psi \rangle (b)\alpha_n$ , we have  $b' = b''\alpha_n$  for some dart  $b'' \in \langle \Psi \rangle (b)$  and we obtain, when  $h_{q+1} \neq n$ , that  $d = b''\alpha_n\alpha_{h_{q+1}} = b''\gamma_{h_{q+1}} \in \langle \Psi \rangle (b)$ . Again, if  $h_{q+1} = n$  we immediately conclude since in this case  $d = b''\alpha_n\alpha_n = b''$ .

Eventually, we have proved that  $d \in \langle \Psi \rangle (b)$  or  $d \in \langle \Psi \rangle (b)\alpha_n$  when the sequence of involutions has a length  $p + 1$ . The property is thus true for any sequence.  $\square$

Later on, we use the fact that a regular cell in  $M$  is associated with a regular cell in  $AG(M)$ . This will be stated by Theorem 4, whose proof is based on the next Lemmas.

**Lemma 9** *If  $\mathcal{C}$  is an  $i$ -cell,  $0 \leq i \leq n - 2$ , in a map that satisfies property a) of Definition 16, then  $\tilde{\mathcal{C}}$  in  $AG(M)$  satisfies property a) of Definition 14.*

*Proof:* Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  and  $G = AG(M) = (\tilde{\mathcal{D}} = \mathcal{D}\mathcal{U}\mathcal{D}', \alpha_0, \dots, \alpha_n)$ .

- If  $i < n - 3$ .

We may write  $\mathcal{C} = \langle \hat{\gamma}_i \rangle (b)$  for some  $b \in \mathcal{D}$ . Following Definition 17 we have  $\tilde{\mathcal{C}} = \mathcal{C} \cup \mathcal{C}\alpha_n$ .

Let  $d \in \tilde{\mathcal{C}}$ .

a) If  $d \in \mathcal{D}$ , by Definition 16 we know that either  $d\gamma_{i+1}\gamma_{i+2} = d\gamma_{i+2}\gamma_{i+1}$  or  $d\gamma_{i+1}\gamma_{i+2} \notin \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\gamma_{i+2}\gamma_{i+1})$ . By Lemma 1 we may write  $d\alpha_n\alpha_{i+1}\alpha_n\alpha_{i+2} = d\alpha_n\alpha_{i+2}\alpha_n\alpha_{i+1}$  or  $d\alpha_n\alpha_{i+1}\alpha_n\alpha_{i+2} \notin \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_n\alpha_{i+2}\alpha_n\alpha_{i+1})$ .

Since  $i + 1 \leq n - 3$  and  $AG(M)$  is an  $n$ -G-map, we have  $b\alpha_n\alpha_{i+1} = b\alpha_{i+1}\alpha_n$  and  $b\alpha_n\alpha_{i+2} = b\alpha_{i+2}\alpha_n$  for all  $b \in \mathcal{D}$ . Hence, either  $d\alpha_{i+1}\alpha_{i+2} = d\alpha_{i+2}\alpha_{i+1}$  or  $d\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ .



Now, if  $d\alpha_{i+1}\alpha_{i+2} \neq d\alpha_{i+2}\alpha_{i+1}$  we have  $d\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ . In this case, let us suppose that  $d\alpha_{i+1}\alpha_{i+2} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ . By Lemma 8, we know that

$$\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1}) \subset \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1}) \cup \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})\alpha_n$$

Thus, either  $d\alpha_{i+1}\alpha_{i+2} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$  or  $d\alpha_{i+1}\alpha_{i+2} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})\alpha_n$ . Since  $d\alpha_{i+1}\alpha_{i+2} = d\gamma_{i+1}\gamma_{i+2} \in \mathcal{D}$  and  $\langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})\alpha_n \subset \mathcal{D}'$  we necessarily have  $d\alpha_{i+1}\alpha_{i+2} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ , a contradiction. Therefore,  $d\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ .

Eventually, we have proved that either  $d\alpha_{i+1}\alpha_{i+2} = d\alpha_{i+2}\alpha_{i+1}$  or  $d\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$  which is property a) of Definition 14.

b) If  $d \in \mathcal{D}'$ , then  $d = d'\alpha_n$  for some dart  $d' \in \mathcal{C}$  (Definition 17). From Definition 16 we know that either  $d\alpha_n\gamma_{i+1}\gamma_{i+2} = d\alpha_n\gamma_{i+2}\gamma_{i+1}$  or  $d\alpha_n\gamma_{i+1}\gamma_{i+2} \notin \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_n\gamma_{i+2}\gamma_{i+1})$ .

If  $d\alpha_n\gamma_{i+1}\gamma_{i+2} = d\alpha_n\gamma_{i+2}\gamma_{i+1}$ , we have:

$$\begin{aligned} d\alpha_n\alpha_n\alpha_{i+1}\alpha_n\alpha_{i+2} &= d\alpha_n\alpha_n\alpha_{i+2}\alpha_n\alpha_{i+1} \quad (\text{Lemma 1}) \\ d\alpha_{i+1}\alpha_n\alpha_{i+2} &= d\alpha_{i+2}\alpha_n\alpha_{i+1} \\ d\alpha_{i+1}\alpha_{i+2}\alpha_n &= d\alpha_{i+2}\alpha_{i+1}\alpha_n \quad (i < n - 3) \\ d\alpha_{i+1}\alpha_{i+2} &= d\alpha_{i+2}\alpha_{i+1} \end{aligned}$$

If  $d\alpha_n\gamma_{i+1}\gamma_{i+2} \neq d\alpha_n\gamma_{i+2}\gamma_{i+1}$ , then  $d\alpha_n\gamma_{i+1}\gamma_{i+2} \notin \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d\alpha_n\gamma_{i+2}\gamma_{i+1})$ . Since  $d\alpha_n \in \mathcal{D}$ , we have proved that  $d\alpha_n\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_n\alpha_{i+2}\alpha_{i+1})$ . Since  $i < n - 3$ ,  $d\alpha_n\alpha_{i+2}\alpha_{i+1} = d\alpha_{i+2}\alpha_{i+1}\alpha_n$  and  $d\alpha_n\alpha_{i+1}\alpha_{i+2} = d\alpha_{i+1}\alpha_{i+2}\alpha_n$ . Furthermore, since  $n \notin \{i, i + 1\}$ ,  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1}\alpha_n) = \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ . It follows that  $d\alpha_{i+1}\alpha_{i+2}\alpha_n \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ , which in turn implies that  $d\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ . Eventually, either  $d\alpha_{i+1}\alpha_{i+2} = d\alpha_{i+2}\alpha_{i+1}$  or  $d\alpha_{i+1}\alpha_{i+2} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d\alpha_{i+2}\alpha_{i+1})$ , which is property a) of Definition 14.

• If  $i = n - 3$ .

a) If  $d \in \mathcal{D}$ . Following Definition 16, either  $d\gamma_{n-2}\gamma_{n-1} = d\gamma_{n-1}^{-1}\gamma_{n-2}$ , or  $d\gamma_{n-2} \notin \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})\gamma_{n-1} \cup \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}\gamma_{n-2})\gamma_{n-1}$ .

If  $d\gamma_{n-2}\gamma_{n-1} = d\gamma_{n-1}^{-1}\gamma_{n-2}$ , by Lemma 1 we deduce that  $d\alpha_n\alpha_{n-2}\alpha_n\alpha_{n-1} = d\alpha_{n-1}\alpha_n\alpha_n\alpha_{n-2}$ . Since  $d\alpha_n\alpha_{n-2} = d\alpha_{n-2}\alpha_n$ , we obtain that  $d\alpha_{n-2}\alpha_{n-1} = d\alpha_{n-1}\alpha_{n-2}$ .

Now, if  $d\gamma_{n-2}\gamma_{n-1} \neq d\gamma_{n-1}^{-1}\gamma_{n-1}$  we necessarily have by Definition 16:

$$d\gamma_{n-2} \notin \left( \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})\gamma_{n-1}^{-1} \cup \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}\gamma_{n-2})\gamma_{n-1} \right) \quad (3)$$

Suppose that  $d\alpha_{n-2}\alpha_{n-1} \in \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_{n-1}\alpha_{n-2})$ , which we may rewrite  $d\alpha_{n-2}\alpha_n\alpha_{n-1} \in \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_{n-1}\alpha_n\alpha_{n-2})$ , or  $d\alpha_n\alpha_{n-2}\alpha_n\alpha_{n-1} \in \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_{n-1}\alpha_n\alpha_{n-2})$ . Since  $d \in \mathcal{D}$  we obtain that  $d\gamma_{n-2}\gamma_{n-1} \in \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})$ .

By Lemma 8, we deduce that  $d\gamma_{n-2}\gamma_{n-1} \in \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2}) \cup \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})\alpha_n$ . Finally, the fact that  $d\gamma_{n-2}\gamma_{n-1} \in \mathcal{D}$  and  $\langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})\alpha_n \subset \mathcal{D}'$  implies that  $d\gamma_{n-2}\gamma_{n-1} \in \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})$ , i.e.  $d\gamma_{n-2} \in \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})\gamma_{n-1}^{-1}$ ; which is a contradiction with (3). Therefore,  $d\alpha_{n-2}\alpha_{n-1} \notin \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_{n-1}\alpha_{n-2})$ .

b) If  $d \in \mathcal{D}'$ , we have  $d = b\alpha_n$  for some  $b \in \mathcal{C}$ . If  $\mathcal{C}$  is regular, since  $d\alpha_n = b \in \mathcal{C}$ , following Definition 16 either  $d\alpha_n\gamma_{n-2}\gamma_{n-1}^{-1} = d\alpha_n\gamma_{n-1}\gamma_{n-2}$ , or  $d\alpha_n\gamma_{n-2} \notin \left( \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\gamma_{n-1}^{-1}\gamma_{n-2})\gamma_{n-1}^{-1} \cup \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\alpha_n\gamma_{n-1}\gamma_{n-2})\gamma_{n-1} \right)$ .

If  $d\alpha_n\gamma_{n-2}\gamma_{n-1}^{-1} = d\alpha_n\gamma_{n-1}\gamma_{n-2}$ , by Lemma 1 we deduce that  $d\alpha_n\alpha_n\alpha_{n-2}\alpha_{n-1}\alpha_n = d\alpha_n\alpha_n\alpha_{n-1}\alpha_n\alpha_{n-2}$ . Since  $d\alpha_n\alpha_{n-2} = d\alpha_{n-2}\alpha_n$ , we obtain that  $d\alpha_{n-2}\alpha_{n-1}\alpha_n = d\alpha_{n-1}\alpha_{n-2}\alpha_n$ , hence  $d\alpha_{n-2}\alpha_{n-1} = d\alpha_{n-1}\alpha_{n-2}$ .

Now, if  $d\alpha_n\gamma_{n-2}\gamma_{n-1}^{-1} \neq d\alpha_n\gamma_{n-1}\gamma_{n-2}$ , it follows (Definition 16) that

$$d\alpha_n\gamma_{n-2} \notin \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\alpha_n\gamma_{n-1}\gamma_{n-2})\gamma_{n-1} \quad (4)$$

Let us suppose that  $d\alpha_{n-2}\alpha_{n-1} \in \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_{n-1}\alpha_{n-2})$ . Since  $n \notin \{n-2, n-3\}$  we have  $\langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_{n-1}\alpha_{n-2}) = \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_{n-1}\alpha_{n-2}\alpha_n)$ .

It follows that

$$d\alpha_n\alpha_n\alpha_{n-2}\alpha_{n-1}\alpha_n \in \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_n\alpha_n\alpha_{n-1}\alpha_{n-2}\alpha_n)$$

Since  $d\alpha_n \in \mathcal{D}$ , by Lemma 1 and from the fact that  $b\alpha_n\alpha_{n-2} = b\alpha_{n-2}\alpha_n$  for all  $b \in \tilde{\mathcal{D}}$ , we obtain

$$d\alpha_n\gamma_{n-2}\gamma_{n-1}^{-1} \in \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_n\gamma_{n-1}\gamma_{n-2})$$

By Lemma 8 and the fact that  $d\alpha_n\gamma_{n-2}\gamma_{n-1}^{-1} \in \mathcal{D}$  we deduce that

$$d\alpha_n\gamma_{n-2}\gamma_{n-1}^{-1} \in \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\alpha_n\gamma_{n-1}\gamma_{n-2})$$

in other words,

$$d\alpha_n\gamma_{n-2} \in \langle \hat{\gamma}_{n-3}, \hat{\gamma}_{n-2} \rangle (d\alpha_n\gamma_{n-1}\gamma_{n-2})\gamma_{n-1}$$

which is a contradiction with (4). Therefore,  $d\alpha_{n-2}\alpha_{n-1} \notin \langle \hat{\alpha}_{n-3}, \hat{\alpha}_{n-2} \rangle (d\alpha_{n-1}\alpha_{n-2})$ .

Eventually, we have proved that condition a) of Definition 14 is satisfied for all  $d \in \tilde{\mathcal{C}}$ .

• If  $i = n - 2$ .

a) If  $d \in \mathcal{D}$ . Following Definition 16, we know that either  $d\gamma_{n-1}^{-1} = d\gamma_{n-1}$  or  $d\gamma_{n-1}^{-1} \notin \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d\gamma_{n-1})$ .

If  $d\gamma_{n-1}^{-1} = d\gamma_{n-1}$ , by Lemma 1 we have  $d\alpha_{n-1}\alpha_n = d\alpha_n\alpha_{n-1}$ .

Now, let us consider the case when  $d\gamma_{n-1}^{-1} \neq d\gamma_{n-1}$ . Necessarily, we have  $d\gamma_{n-1}^{-1} \notin \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d\gamma_{n-1})$ .

Suppose that  $d\alpha_{n-1}\alpha_n \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d\alpha_n\alpha_{n-1})$ . Since  $d \in \mathcal{D}$ , we can write  $d\gamma_{n-1}^{-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d\gamma_{n-1})$ , and using Lemma 8 we obtain that  $d\gamma_{n-1}^{-1} \in \langle \hat{\gamma}_{n-2}, \hat{\gamma}_{n-1} \rangle (d\gamma_{n-1}) \cup \langle \hat{\gamma}_{n-2}, \hat{\gamma}_{n-1} \rangle (d\gamma_{n-1})\alpha_n$ . Since  $d\gamma_{n-1}^{-1} \in \mathcal{D}$  and  $\langle \hat{\gamma}_{n-2}, \hat{\gamma}_{n-1} \rangle (d\gamma_{n-1})\alpha_n \subset \mathcal{D}'$  it follows that  $d\gamma_{n-1}^{-1} \in \langle \hat{\gamma}_{n-2}, \hat{\gamma}_{n-1} \rangle (d\gamma_{n-1})$ , a contradiction. Finally, we obtain that  $d\alpha_{n-1}\alpha_n \notin \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d\alpha_n\alpha_{n-1})$ .

We conclude that either  $d\alpha_{n-1}\alpha_n = d\alpha_n\alpha_{n-1}$  or  $d\alpha_{n-1}\alpha_n \notin \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d\alpha_n\alpha_{n-1})$ , which is property a) of Definition 14.

b) If  $d \in \mathcal{D}'$ , we have  $d = d'\alpha_n$  for some dart  $d' \in \mathcal{D}$ .

Following Definition 16, we again know that either  $d'\gamma_{n-1}^{-1} = d'\gamma_{n-1}$  or  $d'\gamma_{n-1}^{-1} \notin \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d'\gamma_{n-1})$ , i.e.  $d'\gamma_{n-1} \notin \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d'\gamma_{n-1}^{-1})$ .

If  $d'\gamma_{n-1}^{-1} = d'\gamma_{n-1}$  we obtain that  $d\alpha_n\alpha_{n-1}\alpha_n = d\alpha_n\alpha_n\alpha_{n-1}$ , thus  $d\alpha_n\alpha_{n-1}\alpha_n = d\alpha_{n-1}$  or again  $d\alpha_n\alpha_{n-1} = d\alpha_{n-1}\alpha_n$ .

If  $d'\gamma_{n-1}^{-1} \neq d'\gamma_{n-1}$  we have necessarily  $d'\gamma_{n-1} \notin \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d'\gamma_{n-1}^{-1})$ . Indeed, let us suppose that  $d\alpha_{n-1}\alpha_n \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d\alpha_n\alpha_{n-1})$ . Since  $n \notin \{n-2, n-1\}$  we deduce that  $d\alpha_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d\alpha_n\alpha_{n-1})$  and then also that  $d\alpha_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d\alpha_n\alpha_{n-1}\alpha_n)$ . Substituting with  $d = d'\alpha_n$  we obtain  $d'\alpha_n\alpha_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d'\alpha_n\alpha_n\alpha_{n-1}\alpha_n)$ , and finally  $d'\gamma_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d'\gamma_{n-1}^{-1})$ .

However, by Corollary 3, we have

$$\langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d'\gamma_{n-1}^{-1}) \subset \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d'\gamma_{n-1}^{-1}) \cup \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d'\gamma_{n-1}^{-1})\alpha_n$$

As  $d' \in \mathcal{D}$ ,  $\langle \gamma_1, \dots, \gamma_{n-3} \rangle (d' \gamma_{n-1}^{-1}) \subset \mathcal{D}$  and therefore  $\langle \gamma_1, \dots, \gamma_{n-3} \rangle (d' \gamma_{n-1}^{-1}) \alpha_n \subset \mathcal{D}'$ . Since  $d' \gamma_{n-1} \in \mathcal{D}$  and  $d' \gamma_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d' \gamma_{n-1}^{-1})$ , we deduce from the above inclusion that  $d' \gamma_{n-1} \in \langle \gamma_1, \dots, \gamma_{n-3} \rangle (d' \gamma_{n-1}^{-1})$ , a contradiction. Finally,  $d \alpha_{n-1} \alpha_n \notin \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d \alpha_n \alpha_{n-1})$ .

We obtain that property a) of Definition 14 is satisfied by  $\tilde{\mathcal{C}}$ .  $\square$

**Lemma 10** *If  $\mathcal{C}$  is an  $i$ -cell in an  $n$ -map for  $i \leq n - 2$  and such that it satisfies property b) of Definition 16, then  $\tilde{\mathcal{C}}$  in  $AG(M)$  satisfies property b) of Definition 14.*

*Proof:* Let us denote  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  and  $G = AG(M) = (\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}', \alpha_0, \dots, \alpha_n)$ . Furthermore, let  $\mathcal{C}$  be an  $i$ -cell of  $M$  that satisfies property b), and let  $d$  be a dart of  $\tilde{\mathcal{C}}$ .

• If  $i < n - 2$ .

a) If  $d \in \mathcal{D}$ . Suppose that  $d \alpha_{i+1} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$ . By Lemma 8,  $\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d) \subset \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d) \cup \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d) \alpha_n$  so that either  $d \alpha_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d)$  or  $d \alpha_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d) \alpha_n$ . Necessarily, we have  $d \alpha_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d) \alpha_n$  since  $d \alpha_{i+1} \in \mathcal{D}'$ . We deduce that  $d \alpha_{i+1} \alpha_n \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d)$ , i.e.  $d \alpha_n \alpha_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d)$ , since  $i + 1 < n - 1$ . Thus, we have  $d \gamma_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d)$ . But this is a contradiction with the fact that  $\mathcal{C}$  is regular in  $M$  (point  $b$  of Definition 16). Hence,  $d \alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$  which is property b) of Definition 14.

b) If  $d \in \mathcal{D}'$ , we have  $d = b \alpha_n$  for some dart  $b \in \mathcal{C}$ . Suppose that  $d \alpha_{i+1} = b \alpha_n \alpha_{i+1} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b \alpha_n)$ . Since  $n \notin \{i, i + 1\}$  we have  $b \alpha_n \alpha_{i+1} \in \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b)$ . By Lemma 8,

$$\langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (b) \subset \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b) \cup \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b) \alpha_n$$

so either  $b \alpha_n \alpha_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b)$  or  $b \alpha_n \alpha_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b) \alpha_n$ .

Since  $b \alpha_n \alpha_{i+1} \in \mathcal{D}$ , necessarily  $b \alpha_n \alpha_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (b)$ . In other words,  $b \gamma_{i+1} \in \langle \hat{\gamma}_i, \hat{\gamma}_{i+1} \rangle (d)$ , which is a contradiction with the fact that  $b$  belongs to a regular  $i$ -cell of  $M$  (property  $b$ ) of Definition 16). Therefore,  $d \alpha_{i+1} \notin \langle \hat{\alpha}_i, \hat{\alpha}_{i+1} \rangle (d)$  so that property  $b$ ) of Definition 14 is verified.

• If  $i = n - 2$ .

a) If  $d \in \mathcal{D}$ , following Definition 14 we have  $b \gamma_{n-1} \notin \langle \gamma_0, \dots, \gamma_{n-3} \rangle (b)$ .

Now, let us suppose that  $d \alpha_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d)$ . Since  $n \notin \{n-2, n-1\}$  we deduce that  $d \alpha_{n-1} \alpha_n \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d)$  and by Corollary 3 that  $d \gamma_{n-1}^{-1} \in \langle \hat{\gamma}_{n-2}, \hat{\gamma}_{n-1} \rangle (d)$ , which is a contradiction. Thus,  $d \alpha_{n-1} \notin \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d)$ .

b) If  $d \in \mathcal{D}'$ , we have  $d = d'\alpha_n$  for some dart  $d' \in \mathcal{D}$ . Let us suppose that  $d\alpha_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d)$ . We obtain that  $d'\alpha_n\alpha_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d'\alpha_n)$ . Again, since  $n \notin \{n-2, n-1\}$  we have  $d'\alpha_n\alpha_{n-1} \in \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d')$ , and by Corollary 3 (since  $d' \in \mathcal{D}'$ )  $d'\gamma_{n-1} \in \langle \hat{\gamma}_{n-2}, \hat{\gamma}_{n-1} \rangle (d')$ . A contradiction with the fact that  $\mathcal{C}$  is regular (Definition 16). Thus, again  $d\alpha_{n-1} \notin \langle \hat{\alpha}_{n-2}, \hat{\alpha}_{n-1} \rangle (d)$ .

Eventually, condition b) of Definition 14 is satisfied by  $\tilde{\mathcal{C}}$ .  $\square$

**Theorem 4** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and  $AG(M) = (\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}', \alpha_0, \dots, \alpha_n)$  be an associated  $n$ -G-map of  $M$  following Definition 7. If  $\mathcal{C}$  is a regular  $i$ -cell in  $M$  for  $0 \leq i \leq n-2$  (Definition 16), then the associated cell of  $\mathcal{C}$  in  $AG(M)$  is regular (Definition 14).*

*Proof:* If  $\mathcal{C}$  satisfies properties a) and b) of Definition 16 then by Lemma 9  $\tilde{\mathcal{C}}$  satisfies property a) Definition 14 and by Lemma 10 it satisfies property b) of Definition 14. Hence  $\tilde{\mathcal{C}}$  is regular in  $G$ .  $\square$

**Property 4** *An  $(n-1)$ -cell in an  $n$ -map is of degree either 1 or 2. If the  $n$ -map is closed, then all  $(n-1)$ -cells are of degree 2.*

### 3 Cells removal and contraction in G-maps and maps

#### 3.1 Cells removal

**Notation 3** *If  $S = \{E_i\}_{0 \leq i \leq N}$  is a set of sets for  $N \in \mathbb{N}$ , we denote by  $S^*$  the union of sets in  $S$ , i.e.*

$$S^* = \bigcup_{0 \leq i \leq N} E_i$$

**Definition 18 (Removal set)** *Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ -G-map (resp.  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map) and  $S_r = \{R_i\}_{0 \leq i \leq n}$  be sets of  $i$ -cells with  $R_n = \emptyset$ . The family of sets  $S_r$  is called a removal set in  $G$  (resp. in  $M$ ). Furthermore, for such a family we will denote  $R = \bigcup_{i=0}^n R_i$ , the set of all cells of  $S_r$ , so that  $R^*$  is the set of all darts in  $S_r$ .*

**Definition 19 (Removal kernel)** *Let  $G$  be an  $n$ -G-map. A removal kernel  $K_r = \{R_i\}_{0 \leq i \leq n}$  in  $G$  is a removal set such that all cells of  $R$  are disjoint (i.e.  $\forall \mathcal{C}, \mathcal{C}' \in R, \mathcal{C} \cap \mathcal{C}' = \emptyset$ ) and all of them are regular cells with local degree 2 (Definitions 14 and 12). A removal kernel is defined the same way for an  $n$ -map  $M$  using Definitions 16 and 15 for the notions of regularity and local degree, respectively.*

**Lemma 11** *Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ - $G$ -map and  $K_r = \{R_i\}_{0 \leq i \leq n}$  be a removal kernel in  $G$ . We have  $R_i^* \alpha_i \cap R^* \subset R_i^*$  for all  $i$ ,  $0 \leq i \leq n$ .*

*Proof of Lemma 11:* Let  $d' = d\alpha_i$  for  $d \in R_i^*$  (i.e.,  $d' \in R_i^* \alpha_i$ ) and such that  $d' \in R^*$ . We prove that  $d' \in R_i^*$ .

Since  $d' \in R^*$ , it is sufficient to prove that  $d' \notin R_j^*$  for all  $j \neq i$ . Let us suppose that  $d' \in R_j^*$  with  $i \neq j$ , which means that  $d'$  belongs to a  $j$ -cell  $\mathcal{C}_j \in R_j$ :

$$d' \in \langle \alpha_0, \dots, \hat{\alpha}_j, \dots, \alpha_n \rangle (d''), \quad d'' \in R_j^*$$

Since  $i \neq j$ ,  $d' \alpha_i$  also belongs to the above  $j$ -cell. However,  $d' \alpha_i = d\alpha_i \alpha_i = d \in R_i^*$ . We have exhibited a dart which belongs to both a removed  $j$ -cell and a removed  $i$ -cell. This is a contradiction with the fact that cells of  $R$  do not intersect (Definition 19).  $\square$

**Corollary 5** *Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ - $G$ -map and  $K_r = \{R_i\}_{0 \leq i \leq n}$  be a removal kernel in  $G$ . With  $\mathcal{D}' = \mathcal{D} \setminus R^*$  we have for all  $i \in \{0, \dots, n\}$ :*

$$R_i^* \alpha_i \setminus R_i^* \subset \mathcal{D}' \quad \text{and} \quad R_i^* \alpha_i \cap \mathcal{D}' = R_i^* \alpha_i \setminus R_i^* \quad (5)$$

*Proof:* From Lemma 11, we know that  $R_i^* \alpha_i \cap R^* \subset R_i^*$ . We deduce that  $R_i^* \alpha_i \setminus R_i^* \subset R_i^* \alpha_i \setminus R^*$ . On the other hand,  $R_i^* \subset R^*$  implies that  $R_i^* \alpha_i \setminus R^* \subset R_i^* \alpha_i \setminus R_i^*$ . It follows that  $R_i^* \alpha_i \setminus R^* = R_i^* \alpha_i \setminus R_i^*$ . Furthermore, since  $R_i^* \alpha_i \setminus R^*$  is a subset of  $\mathcal{D}' = \mathcal{D} \setminus R^*$  we also have  $R_i^* \alpha_i \setminus R_i^* \subset \mathcal{D}'$ .

On the other hand, let us write:

$$R_i^* \alpha_i \cap \mathcal{D}' = R_i^* \alpha_i \cap (\mathcal{D} \setminus R^*) = (R_i^* \alpha_i \cap \mathcal{D}) \setminus R^* = R_i^* \alpha_i \setminus R^*$$

As shown above, we have  $R_i^* \alpha_i \setminus R^* = R_i^* \alpha_i \setminus R_i^*$ . Finally, we obtain that  $R_i^* \alpha_i \cap \mathcal{D}' = R_i^* \alpha_i \setminus R_i^*$ .  $\square$

The following definition for cells removal is adapted from [6] where a definition combining removals and contractions is given. The definition below is obtained by considering that no cell is to be contracted.

In her definition, Grasset required that cells of the removal kernel should have a local degree two according to her definition (Definition 13). We have seen that this definition is both too restrictive to be a valid definition for the local degree 2, but also that it does not exclude cells with local degree 1.

We know that excluding cells with local degree 1 from Grasset's definition yields the notion of *regular cells* with local degree 2 (Definition 14). Both notions being equivalent, as shown by Theorem 1. Therefore, the definition

we present below as a note, although not exactly the one given by Grasset, is just more restrictive in the sense that no cell with a local degree one should be in the removal kernel.

**Note 1** *The operation of cells removal in  $n$ -G-maps is defined as follows in [6]: Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ -G-map and  $K_r = \{R_i\}_{0 \leq i \leq n-1}$  a removal kernel in  $G$ . Let  $BV_i = R_i^* \alpha_i \setminus R_i^*$ ,  $\forall i, 0 \leq i \leq n$ . The set  $BV_i$  is called the set of surviving darts which are neighbors of an  $i$ -cell to be removed. The  $n$ -G-map resulting of the removal of the cells of  $R$  is  $G' = (\mathcal{D}', \alpha'_0, \dots, \alpha'_n)$  defined by:*

- (1)  $\mathcal{D}' = \mathcal{D} \setminus R^*$ ;
- (2)  $\forall i, 0 \leq i \leq n, \forall b \in \mathcal{D}' \setminus BV_i, b\alpha'_i = b\alpha_i$ ;
- (3)  $\forall i, 0 \leq i < n, \forall b \in BV_i, b\alpha'_i = b' = b(\alpha_i \alpha_{i+1})^k \alpha_i$  where  $k$  is the smallest integer such that  $b' \in BV_i$ .

In this report, we use the following definition for the removal of cells, definition which is proved to be equivalent to the one used in [6].

**Definition 20 (Cells removal in  $n$ -G-maps)** *Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ -G-map and  $K_r = \{R_i\}_{0 \leq i \leq n-1}$  be a removal kernel in  $G$ . The  $n$ -G-map resulting of the removal of the cells of  $R$  is  $G' = (\mathcal{D}', \alpha'_0, \dots, \alpha'_n)$  where:*

- (1)  $\mathcal{D}' = \mathcal{D} \setminus R^*$ ;
- (2)  $\forall d \in \mathcal{D}', d\alpha'_n = d\alpha_n$ ;
- (3)  $\forall i, 0 \leq i < n, \forall d \in \mathcal{D}', d\alpha'_i = d' = d(\alpha_i \alpha_{i+1})^k \alpha_i$  where  $k$  is the smallest integer such that  $d' \in \mathcal{D}'$ .

**Notation 4** *The  $n$ -G-map obtained after removal of a kernel  $K_r = \{R_i\}_{0 \leq i \leq n}$  from an  $n$ -G-map  $G$  will be denoted either by  $G \setminus K_r$ , or by  $G \setminus R^*$ .*

As stated by the next proposition, the involution  $\alpha_n$  remains unchanged after the removal operation.

**Proposition 9** *Let  $G, G'$  be  $n$ -G-maps and  $K_r = \{R_i\}_{0 \leq i \leq n}$  be a removal kernel as in Definition 20. Since  $R_n = \emptyset$ , then  $d\alpha_n \in \mathcal{D}'$  for all  $d \in \mathcal{D}'$ .*

*Proof:* It is readily seen that  $d\alpha_n \in \mathcal{D}'$  for all  $d \in \mathcal{D}'$ . Indeed, suppose that  $d\alpha_n \in \mathcal{C}_i \in R_i$  for some  $i \in \{0, \dots, n-1\}$ . In other words,  $d\alpha_n$  belongs to an  $i$ -cell which is to be removed for  $i < n$ :

$$\mathcal{C}_i = \langle \alpha_0, \dots, \hat{\alpha}_i, \dots, \alpha_n \rangle (d\alpha_n) \in R_i, 0 \leq i < n$$

Since  $i < n$ , we deduce that  $d\alpha_n \alpha_n = d$  also belongs to the above orbit, thus  $d$  belongs to the same  $i$ -cell of  $R_i$ . This is a contradiction with the fact that  $d \in \mathcal{D}'$ .  $\square$

**Remark 5** Let  $G, G'$  be  $n$ - $G$ -maps and  $K_r = \{R_i\}_{0 \leq i \leq n}$  be a removal kernel as in Definition 20. If a dart  $d$  belongs to an  $i$ -cell  $\mathcal{C}$  of  $R_i$ , then  $d\alpha_n \in \mathcal{C}$ . Indeed, since there are no  $n$ -cell in  $K_r$ ,  $i < n$  so that  $d\alpha_n \in \langle \hat{\alpha}_i \rangle (d) = \mathcal{C}$ .

The equivalence between Definition 10 of [6] (see Note 1) and Definition 20 is stated by Proposition 10. The next two lemmas will be used in the proof of the proposition.

**Lemma 12** Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ - $G$ -map and  $K_r = \{R_i\}_{0 \leq i \leq n-1}$  be a removal kernel in  $G$ . Let  $i \in \{0, \dots, n-1\}$  and  $d \in R_i^* \alpha_i \setminus R_i^*$ . If  $k$  is the smallest integer such that  $d' = d(\alpha_i \alpha_{i+1})^k \alpha_i \in \mathcal{D} \setminus R^*$ , then  $k > 0$  and for all  $0 \leq h < k$  we have  $d(\alpha_i \alpha_{i+1})^h \alpha_i \in R_i^*$ .

*Proof:* Let  $\mathcal{D}' = \mathcal{D} \setminus R^*$ . We first show that  $k > 0$ . Indeed,  $d \in R_i^* \alpha_i \setminus R_i^*$  means that  $d = b\alpha_i$  for some dart  $b \in R_i^*$  so that  $d\alpha_i = b\alpha_i \alpha_i = b \in R_i^*$ . Therefore,  $d\alpha_i \notin \mathcal{D}'$  so  $k$  cannot be equal to 0.

Then, we prove by recurrence on  $h$ ,  $0 \leq h < k$  that  $d(\alpha_i \alpha_{i+1})^h \alpha_i \in R_i$ , assuming that it does not belong to  $\mathcal{D}'$  since  $h < k$ . The property has already been shown to be true for  $h = 0$ .

Let us suppose that  $d'' = d(\alpha_i \alpha_{i+1})^h \alpha_i$  belongs to  $R_i^*$ . Therefore,  $d''$  belongs to a removed  $i$ -cell, say  $\mathcal{C}_i = \langle \alpha_0, \dots, \hat{\alpha}_i, \dots, \alpha_n \rangle (d'')$ . Because  $i + 1 \neq i$  we deduce that  $d''\alpha_{i+1} = d(\alpha_i \alpha_{i+1})^h \alpha_i \alpha_{i+1} = d(\alpha_i \alpha_{i+1})^{h+1} \in \mathcal{C}_i \in R_i$ . Now, consider  $d' = d(\alpha_i \alpha_{i+1})^{h+1} \alpha_i$  and suppose it does not belong to  $\mathcal{D}'$  ( $h + 1 < k$ ). There are two cases: either it belongs to  $R_i^*$  or it belongs to  $R_j^*$ ,  $j \neq i$ . In the latter case we observe that  $d(\alpha_i \alpha_{i+1})^{h+1} \alpha_i$  and  $d(\alpha_i \alpha_{i+1})^{h+1}$  belong to the same  $j$ -cell. Therefore,  $d(\alpha_i \alpha_{i+1})^{h+1} \alpha_i \in \mathcal{C}' \in R_j$  implies that  $d(\alpha_i \alpha_{i+1})^{h+1} \in \mathcal{C}'$  which contradicts the fact that  $d(\alpha_i \alpha_{i+1})^{h+1} \in \mathcal{C}_i \in R_i$  since cells to be removed are disjoint (Definition 19). Hence,  $d(\alpha_i \alpha_{i+1})^{h+1} \alpha_i \in R_i$  and the property is true for  $h + 1$ .  $\square$

**Lemma 13** Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ - $G$ -map and  $K_r = \{R_i\}_{0 \leq i \leq n-1}$  be a removal kernel in  $G$ . Let  $\mathcal{D}' = \mathcal{D} \setminus R^*$ ,  $i \in \{0, \dots, n-1\}$  and  $BV_i = R_i^* \alpha_i \setminus R_i^*$ . If  $d \in \mathcal{D}' \setminus BV_i$  then  $d\alpha_i \in \mathcal{D}'$ .

*Proof:* We need to prove that  $d\alpha_i \notin R^*$  when  $d \notin R^*$  and  $d \notin BV_i$ .

We first show that  $d\alpha_i \notin R_i^*$ . Indeed, if we suppose that  $d\alpha_i \in R_i^*$ , then  $d\alpha_i \alpha_i = d \in R_i^* \alpha_i$ . Since  $d \notin R^*$ , in particular  $d \in R_i^* \alpha_i \setminus R^* = R_i^* \alpha_i \setminus R_i^*$  (Corollary 5), i.e.  $d \in BV_i^*$  and it follows that  $d \in BV_i$  which is a contradiction, thus  $d\alpha_i \notin R_i^*$ .

We also prove that  $d\alpha_i \notin R_j^*$  for all  $j$ ,  $j \neq i$ . Indeed, if  $d\alpha_i \in \mathcal{C}_j = \langle \alpha_0, \dots, \hat{\alpha}_j, \dots, \alpha_n \rangle (b)$  for  $b \in R_j^*$  then since  $i \neq j$ ,  $d\alpha_i \alpha_i = d$  also belongs to  $\mathcal{C}_j$ . This is a contradiction with the fact that  $d \in \mathcal{D}'$ . Finally, we have  $d\alpha_i \notin R^*$



so  $d\alpha_i \in \mathcal{D}'$ .  $\square$

**Proposition 10** *Definition 20 and the one given in Note 1 are equivalent.*

*Proof:* We need to check that the involutions  $\alpha'_i$  coincide in both definitions for all  $i$ ,  $0 \leq i \leq n$ .

For  $i = n$ , only case (2) in Note 1 applies and  $\mathcal{D}' \setminus \text{BV}_n = \mathcal{D}'$  since  $\text{BV}_n = \emptyset$ . This point thus defines  $b\alpha'_n = b\alpha_n$  for all  $b \in \mathcal{D}'$  which is precisely point (2) of Definition 20.

It remains the case when  $0 \leq i < n$ . Let  $d \in \mathcal{D}'$ , we distinguish two cases:

1) If  $d \notin \text{BV}_i$  then from Lemma 13 we have  $d\alpha_i \in \mathcal{D}'$ . Thus,  $k = 0$  is the smallest integer such that  $d' \in \mathcal{D}'$  in point (3) of Definition 20 so that  $d\alpha'_i = d' = d\alpha_i$  is defined as in point (2) of Note 1.

2) Next, we consider the case when  $d \in \text{BV}_i$ . We define

$$\begin{aligned} k_1 &= \min\{h \in \mathbb{N} \mid d(\alpha_i\alpha_{i+1})^h\alpha_i \in \text{BV}_i\} \\ k_2 &= \min\{h \in \mathbb{N} \mid d(\alpha_i\alpha_{i+1})^h\alpha_i \in \mathcal{D}'\} \end{aligned}$$

Since  $\text{BV}_i \subset \mathcal{D}'$  (Corollary 5) we have  $k_2 \leq k_1$ .

From Lemma 12, we know that for all  $0 \leq h < k_2$  we have  $d(\alpha_i\alpha_{i+1})^h\alpha_i \in R_i^*$ . In particular,  $d(\alpha_i\alpha_{i+1})^{k_2-1}\alpha_i \in R_i^*$ . Because applying  $\alpha_{i+1}$  cannot send a dart from an  $i$ -cell to another  $i$ -cell we deduce that  $d(\alpha_i\alpha_{i+1})^{k_2-1}\alpha_i\alpha_{i+1} = d(\alpha_i\alpha_{i+1})^{k_2} \in R_i^*$ . Therefore, we have  $d(\alpha_i\alpha_{i+1})^{k_2}\alpha_i \in R_i^*\alpha_i$ . Now, because  $d(\alpha_i\alpha_{i+1})^{k_2}\alpha_i \in \mathcal{D}'$  we thus have  $d(\alpha_i\alpha_{i+1})^{k_2}\alpha_i \in R_i^*\alpha_i \cap \mathcal{D}'$  and from Corollary 5 we obtain that  $d(\alpha_i\alpha_{i+1})^{k_2}\alpha_i \in \text{BV}_i$ . It follows that  $k_2 \geq k_1$ .

Eventually,  $k_1 = k_2$  so that point (3) of Definition 20 is equivalent to point (3) of Note 1 when  $d \in \text{BV}_i$ .  $\square$

**Definition 21 (Cells removal in  $n$ -maps)** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and  $S_r = \{R_i\}_{0 \leq i \leq n-1}$  a removal set in  $M$ . We define the  $(n-1)$ -tuple  $M \setminus S_r = (\mathcal{D}', \gamma'_0, \dots, \gamma'_{n-1})$  obtained after removal of the cells of  $S_r$  by:*

- $\mathcal{D}' = \mathcal{D} \setminus R^*$ ;
- $\forall i \in \{0, \dots, n-2\}, \forall d \in \mathcal{D}', d\gamma'_i = d(\gamma_i\gamma_{i+1}^{-1})^k\gamma_i$ , where  $k$  is the smallest integer such that  $d(\gamma_i\gamma_{i+1}^{-1})^k\gamma_i \in \mathcal{D}'$ .
- For  $i = n-1, \forall d \in \mathcal{D}', d\gamma'_{n-1} = d\gamma_{n-1}^{k+1}$  where  $k$  is the smallest integer such that  $d\gamma_{n-1}^{k+1} \in \mathcal{D}'$ .

We will prove in the sequel (Theorem 6) that the such defined  $(n - 1)$ -tuple  $M \setminus S_r$  is actually an  $n$ -map if  $S_r$  is a removal kernel (Definition 19), this by establishing the link between removal in  $n$ -maps and removal in  $n$ -G-maps. Note that until this result has been proved, in the notation  $M' = M \setminus K_r$ , the prime indicates that  $M'$  is linked to a map but is not necessarily itself a map.

**Definition 22** *Let  $G$  be an  $n$ -G-map,  $S_r = \{R_i\}_{0 \leq i \leq n}$  be a removal set in  $G$  and  $M = HV(G)$ . We define the set  $HV(S_r) = \{R'_i\}_{0 \leq i \leq n}$  as follows:*

- $\forall i \in \{0, \dots, n - 1\}$ ,  $R'_i = \{ \langle \alpha_n \alpha_0, \dots, \alpha_n \hat{\alpha}_i, \dots, \alpha_n \alpha_{n-1} \rangle (d) \mid d \in R_i^* \}$
- $R'_n = \{ \langle \alpha_0 \alpha_1, \dots, \alpha_0 \alpha_{n-1} \rangle (d) \mid \exists \mathcal{C} \in R_n, d \in \mathcal{C} \}$

**Lemma 14** *Let  $G$  be an  $n$ -G-map,  $S_r = \{R_i\}_{0 \leq i \leq n}$  be a removal set in  $G$  and  $M = HV(G)$ . If  $HV(S_r) = \{R'_i\}_{0 \leq i \leq n}$ , we have  $R^* = R'^*$ .*

*Proof:* The fact that  $R^* \subset R'^*$  is immediate. Indeed, since  $d \in \langle \alpha_n \alpha_0, \dots, \alpha_n \hat{\alpha}_i, \dots, \alpha_n \alpha_{n-1} \rangle (d)$ , any dart of a cell of  $R_i$  (for  $0 \leq i \leq n - 1$ ) belongs to  $R'_i$ .

On the other hand, for all  $d \in \mathcal{D}$  and all  $i \in \{0, \dots, n - 1\}$  we have

$$\langle \alpha_n \alpha_0, \dots, \alpha_n \hat{\alpha}_i, \dots, \alpha_n \alpha_{n-1} \rangle (d) \subset \langle \alpha_n, \dots, \hat{\alpha}_i, \dots, \alpha_{n-1}, \alpha_n \rangle (d) \quad (6)$$

From the definition of  $R'_i$ , if  $E = \langle \alpha_n \alpha_0, \dots, \alpha_n \hat{\alpha}_i, \dots, \alpha_n \alpha_{n-1} \rangle (d) \in R'_i$  there exists an  $i$ -cell  $\mathcal{C}$  in  $R_i$  such that  $d \in \mathcal{C}$ . The  $i$ -cell of  $G$  that contains  $d$  is  $\langle \alpha_n, \dots, \hat{\alpha}_i, \dots, \alpha_{n-1}, \alpha_n \rangle (d)$ . From (6) we deduce that  $E \subset \mathcal{C}$ . Finally,  $R'^* \subset R^*$ .  $\square$

**Lemma 15** *If  $G$  is an  $n$ -G-map and  $S_r$  is a removal set in  $G$ , then the set  $HV(S_r)$  is a removal set in  $HV(G)$ .*

*Proof:* Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$ , according to Definition 5  $HV(G) = (\mathcal{D}, \gamma_0 = \alpha_n \alpha_0, \dots, \gamma_{n-1} = \alpha_n \alpha_{n-1})$ .

From the definition of  $HV(S_r)$ , it is immediate that  $R'_n = \emptyset$ . Now, for all  $i \in \{0, \dots, n - 1\}$  and all  $E \in R'_i$ , we have  $E = \langle \alpha_n \alpha_0, \dots, \alpha_n \hat{\alpha}_i, \dots, \alpha_n \alpha_{n-1} \rangle (d)$ , for some dart  $d \in \mathcal{D}$ . Thus,  $E$  is an  $i$ -cell in  $HV(G)$ , from the very definition of  $i$ -cells in maps. It follows that  $HV(S_r)$  is a removal set in  $HV(G)$ .  $\square$

The next proposition is a first step to show that our definition of cells removal in  $n$ -maps is consistent with the one of removal in  $n$ -G-maps.

It remains to be proved that the removal operation, when applied to an  $n$ -map, produces a valid  $n$ -map as soon as the cells to be removed constitute a removal kernel according to Definition 19. A consequence of Proposition 11 is that this is true when the map is the map of the hypervolumes of an  $n$ -G-map, not for

any map. The extension of Proposition 11 to any map will be the purpose of Theorem 6.

**Proposition 11** *If  $G$  is an  $n$ -G-map and  $K_r$  is a removal kernel in  $G$ , we have the following commutative diagram:*

$$\begin{array}{ccc} G & \xrightarrow{\text{removal of } K_r} & G' = G \setminus K_r \\ HV \downarrow & & HV \downarrow \\ M & \xrightarrow{\text{removal of } HV(K_r)} & M \setminus HV(K_r) \end{array}$$

*In particular,  $M \setminus HV(K_r)$  is an  $n$ -map.*

*Proof of Proposition 11:* Let  $G, G'$  be the  $n$ -G-maps and  $K_r$  be the removal kernel as in Definition 20. By Lemma 15,  $HV(K_r)$  is a proper removal set in  $HV(G)$ . If  $M = HV(G)$ , we want to prove that the  $n$ -map  $M'_1$  obtained after removal of  $HV(K_r)$  from  $M$  is precisely  $M'_2 = HV(G')$ , the map of hypervolumes of  $G' = G \setminus K_r$ .

Let us write  $K_r = \{R_i\}_{0 \leq i \leq n}$  and  $S_r = HV(K_r) = \{R'_i\}_{0 \leq i \leq n}$ .

Let  $\mathcal{D}' = \mathcal{D} \setminus R^*$  (By Lemma 14,  $\mathcal{D}' = \mathcal{D} \setminus R'^*$ ). We have:

- $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$ ;
- $G' = (\mathcal{D}', \alpha'_0, \dots, \alpha'_n)$  where  $\alpha'_i$  for  $0 \leq i \leq n$  follows Definition 20;
- $M = HV(G) = (\mathcal{D}, \gamma_0 = \alpha_n \alpha_0, \dots, \gamma_{n-1} = \alpha_n \alpha_{n-1})$ , from Definition 5;
- $M'_2 = HV(G') = (\mathcal{D}', \gamma''_0 = \alpha'_n \alpha'_0, \dots, \gamma''_{n-1} = \alpha'_n \alpha'_{n-1})$ , from Definition 5;
- $M'_1 = (\mathcal{D}', \gamma'_0, \dots, \gamma'_{n-1})$  is the  $n$ -map obtained after removal of cells of  $R'$  from  $M$  (following Definition 21).

We need to prove that for all  $i \in \{0, \dots, n-1\}$  and for all  $d \in \mathcal{D}'$ ,  $d\gamma'_i = d\gamma''_i$  which will eventually show that  $M'_1 = M'_2$ .

Let  $d \in \mathcal{D}'$  and  $i \in \{0, \dots, n-1\}$ .

– If  $i \leq n-2$ , following Definition 21,  $d\gamma'_i = d(\gamma_i \gamma_{i+1}^{-1})^k \gamma_i$  where  $k$  is the smallest integer such that  $d(\gamma_i \gamma_{i+1}^{-1})^k \gamma_i \notin R^*$ . Since  $\gamma_i = \alpha_n \alpha_i$  for  $0 \leq i \leq n-1$  we obtain:

$$d\gamma'_i = d(\alpha_n \alpha_i (\alpha_n \alpha_{i+1})^{-1})^k \alpha_n \alpha_i = d(\alpha_n \alpha_i \alpha_{i+1} \alpha_n)^k \alpha_n \alpha_i$$

Since  $\alpha_n^2 = 1_{\mathcal{D}}$  the latter equality becomes:

$$d\gamma'_i = d\alpha_n (\alpha_i \alpha_{i+1})^k \alpha_i$$

In the same way, we have for all  $h < k$ ,  $d(\gamma_i \gamma_{i+1}^{-1})^h \gamma_i = d\alpha_n(\alpha_i \alpha_{i+1})^h \alpha_i \in R^*$ . It follows that  $k$  is also the smallest exponent such that  $d\alpha_n(\alpha_i \alpha_{i+1})^k \alpha_i \in R^*$ .

On the other hand  $\gamma_i'' = \alpha'_n \alpha'_i$ . According to Definition 20 we have for any dart  $b \in \mathcal{D}'$ ,  $b\alpha'_n = b\alpha_n$  and  $b\alpha'_i = b' = b(\alpha_i \alpha_{i+1})^r \alpha_i$  where  $r$  is the smallest integer such that  $b' \in \mathcal{D}'$ . Eventually, we have  $d\gamma_i'' = d\gamma'_i$ .

– If  $i = n - 1$  then  $d\gamma'_{n-1} = d\gamma_{n-1}^{k+1}$  where  $k$  is the smallest integer such that  $d\gamma_{n-1}^{k+1} \in \mathcal{D}'$ . Since  $\gamma_{n-1} = \alpha_n \alpha_{n-1}$  we have

$$d\gamma'_{n-1} = d(\alpha_n \alpha_{n-1})^{k+1} = d\alpha_n(\alpha_{n-1} \alpha_n)^k \alpha_{n-1}$$

In the same way, we have for all  $h < k+1$ ,  $d\gamma_{n-1}^h = d\alpha_n(\alpha_{n-1} \alpha_n)^h \alpha_{n-1} \in R^*$ . It follows that  $k$  is also the smallest exponent such that  $d\alpha_n(\alpha_{n-1} \alpha_n)^h \alpha_{n-1} \in R^*$ .

On the other hand  $\gamma_{n-1}'' = \alpha'_n \alpha'_{n-1}$  where  $\alpha'_{n-1}$  is defined for all  $b \in \mathcal{D}'$  by  $b\alpha'_{n-1} = b' = b(\alpha_{n-1} \alpha_n)^r \alpha_{n-1}$  where  $r$  is the smallest integer such that  $b' \in \mathcal{D}'$ . Again, since  $d\alpha'_n = d\alpha_n$  (Definition 20) we have  $d\gamma_{n-1}'' = d\alpha_n(\alpha_{n-1} \alpha_n)^r \alpha_{n-1}$ . Eventually,  $d\gamma_{n-1}'' = d\gamma'_{n-1}$ .  $\square$

**Definition 23 (Associated removal set)** *If  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  is an  $n$ -map and  $K_r = \{R_i\}_{i=0, \dots, n}$  is a removal kernel in  $M$ . Let  $\tilde{G} = AG(M) = (\tilde{\mathcal{D}}, \alpha_0, \dots, \alpha_n)$  be an associated  $n$ -G-map of  $M$ . We define the removal set  $\tilde{K}_r = \{\tilde{R}_i\}_{i=0, \dots, n}$  in  $\tilde{G}$  as follows:*

$$\forall i \in \{0, \dots, n-1\}, \tilde{R}_i = \{\tilde{\mathcal{C}} \mid \mathcal{C} \in R_i\}$$

where  $\tilde{\mathcal{C}}$ , for any cell  $\mathcal{C}$  of  $M$ , is the associated cell of  $\mathcal{C}$  in  $AG(M)$  (Definition 17).

As stated by Proposition 12, the removal set introduced in the previous definition is in fact a removal kernel.

**Lemma 16** *If  $\mathcal{C}_1$  and  $\mathcal{C}_2$  are disjoint cells in  $M$ , then  $\tilde{\mathcal{C}}_1$  and  $\tilde{\mathcal{C}}_2$  are disjoint cells of  $AG(M)$ .*

*Proof:* Following Definition 17 and the notations of Definition 7:

- If  $\mathcal{C}_1$  and  $\mathcal{C}_2$  are both  $i$ -cells with  $i < n$  we have  $\tilde{\mathcal{C}}_1 = \mathcal{C}_1 \cup \mathcal{C}_1 \sigma$  and  $\tilde{\mathcal{C}}_2 = \mathcal{C}_2 \cup \mathcal{C}_2 \sigma$ . Since  $\mathcal{C}_1 \cap \mathcal{C}_2 = \emptyset$  and  $\sigma$  is one-to-one, it follows that  $\mathcal{C}_1 \sigma \cap \mathcal{C}_2 \sigma = \emptyset$ . Now, for any cell  $\mathcal{C} \subset \mathcal{D}$  and  $\mathcal{C} \sigma \subset \mathcal{D}'$  with  $\mathcal{D} \cap \mathcal{D}' = \emptyset$ . It follows that  $\mathcal{C}_1 \cap \mathcal{C}_2 \sigma = \mathcal{C}_2 \cap \mathcal{C}_1 \sigma = \emptyset$ . Eventually, we obtain  $\tilde{\mathcal{C}}_1 \cap \tilde{\mathcal{C}}_2 = \emptyset$ .
- If  $\mathcal{C}_1$  is an  $i$ -cell with  $i < n$  and  $\mathcal{C}_2$  is an  $n$ -cell we have  $\tilde{\mathcal{C}}_1 = \mathcal{C}_1 \cup \mathcal{C}_1 \sigma$  and  $\tilde{\mathcal{C}}_2 = \mathcal{C}_2 \cup \mathcal{C}_2 \gamma_0 \sigma$ , the same arguments apply since  $\gamma_0 \sigma$  is one-to-one and  $\mathcal{C} \gamma_0 \sigma \subset \mathcal{D}'$  for all cells  $\mathcal{C}$  of  $M$ .

- Same considerations apply if  $\mathcal{C}_1$  and  $\mathcal{C}_2$  are both  $n$ -cell.

□

**Proposition 12** *The removal set  $\tilde{K}_r$  in Definition 23 is a removal kernel in  $AG(M)$ .*

*Proof:* Since  $K_r$  is a removal kernel, by Proposition 8 all cells of  $\tilde{K}_r$  have a local degree 2 and by Theorem 4 they are regular. By Lemma 16, if two cells of  $K_r$  are disjoint then their associated cells (in  $\tilde{K}_r$ ) are disjoint too. Thus,  $\tilde{K}_r$  is a removal kernel in  $AG(M)$  according to Definition 19. □

**Definition 24 (Associated removal kernel)** *Let  $M$  be an  $n$ -map and  $AG(M)$  be an associated  $G$ -map of  $M$ . If  $K_r$  is a removal kernel in  $M$ , the set  $\tilde{K}_r$  (Definition 23) is called the removal kernel associated with  $K_r$  in  $AG(M)$  (following Proposition 12).*

**Definition 25 (Removal set restriction)** *If  $S_r = \{R_i\}_{0 \leq i \leq n}$  is a removal set in an  $n$ -map  $M$  and  $\mathcal{D}'$  is a connected component of  $M$ , we denote by  $S_{r|\mathcal{D}'}$  the removal set that contains all the cells of  $S_r$  included in  $\mathcal{D}'$ .*

**Remark 6** *In Definition 25, since  $\mathcal{D}'$  is a connected component, a cell of  $S_r$  is included in  $\mathcal{D}'$  as soon as one of its darts belongs to  $\mathcal{D}'$ . Indeed, any cell of  $\langle \gamma_0, \dots, \gamma_{n-1} \rangle(d)$  belongs to the same connected component of  $M$  as  $d$ .*

**Proposition 13** *If  $M$  is an  $n$ -map,  $K_r$  is a removal set in  $M$ , and  $\mathcal{D}'$  is a connected component of  $M$ , we have the following diagram:*

$$\begin{array}{ccc} M & \xrightarrow{\text{removal of } K_r} & M \setminus K_r \\ \downarrow |_{\mathcal{D}'} & & \downarrow |_{\mathcal{D}'} \\ M' & \xrightarrow{\text{removal of } K_{r|\mathcal{D}'}} & M' \setminus K_{r|\mathcal{D}'} \end{array}$$

*Proof:* Following Remark 3 and Definition 8,  $M' = M|_{\mathcal{D}'}$  and the sub-map of  $M \setminus K_r$  induced by  $\mathcal{D}'$  are both  $n$ -maps.

We now have to prove that the diagram commutes. Let us denote:

$$\begin{aligned} M &= (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1}), \quad M' = (\mathcal{D}', \gamma_{0|\mathcal{D}'}, \dots, \gamma_{n-1|\mathcal{D}'}); \\ M \setminus K_r &= (\mathcal{D}'', \gamma''_0, \dots, \gamma''_{n-1}); \quad \text{and} \\ M' \setminus K_{r|\mathcal{D}'} &= (\mathcal{D}''', \gamma'''_0, \dots, \gamma'''_{n-1}). \end{aligned}$$

We show that for all  $i \in \{0, \dots, n-1\}$ ,  $\gamma'''_i = \gamma''_i|_{\mathcal{D}'}$ .

Let  $K_r = \{R_j\}_{0 \leq j \leq n-1}$  and  $K_r|_{\mathcal{D}'} = \{R'_j\}_{0 \leq j \leq n-1}$ . Furthermore, let  $i \in \{0, \dots, n-1\}$  and  $d \in \mathcal{D}'$ .

In the definition of  $d\gamma_i'''$  (Definition 21),  $d(\gamma_i|_{\mathcal{D}'}\gamma_{i+1}|_{\mathcal{D}'})^{-1})^k\gamma_i|_{\mathcal{D}'}$  ( $d\gamma_{n-1}^{k+1}|_{\mathcal{D}'}$  when  $i = n-1$ ) belongs to  $\mathcal{D}' \setminus R^*$  iff it belongs to  $\mathcal{D} \setminus R^*$ .

Indeed, let us denote  $d' = d(\gamma_i|_{\mathcal{D}'}\gamma_{i+1}|_{\mathcal{D}'})^{-1})^k\gamma_i|_{\mathcal{D}'}$  (resp.  $d\gamma_{n-1}^{k+1}|_{\mathcal{D}'}$ ).

– ( $d' \in \mathcal{D}' \setminus R^* \Rightarrow d' \in \mathcal{D} \setminus R^*$ ) If  $d' \in \mathcal{D}' \setminus R^*$ , in particular  $d' \in \mathcal{D}$  so we have to show that  $d' \notin R^*$ . Now, if  $b$  is a dart of a cell of  $R$  (i.e.  $d \in R^*$ ) such that  $d \in \mathcal{D}'$ , the fact that  $\mathcal{D}'$  is a connected component implies that the cell that contains  $b$  is itself included in  $R$  (Remark 6), thus it also belongs to  $R'$  from the very definition of  $K_r|_{\mathcal{D}'}$ . Therefore, we have  $R^* \cap \mathcal{D}' \subset R'^* \cap \mathcal{D}'$ . It follows that  $d' \notin R'^*$  implies  $d' \notin R^*$ .

– ( $d' \in \mathcal{D} \setminus R^* \Rightarrow d' \in \mathcal{D}' \setminus R^*$ ) Since  $d' \in \mathcal{D}'$ ,  $d' \in \mathcal{D} \setminus R^*$  iff  $d' \in \mathcal{D}' \setminus R^*$  and the implication is straightforward since  $R'^* \subset R^*$ .

It follows that  $d\gamma_i''' = d\gamma_i''$  when  $d \in \mathcal{D}'$ , thus  $\gamma_i''|_{\mathcal{D}'} = \gamma_i'''$ . Eventually, we obtain that  $(M \setminus K_r)|_{\mathcal{D}'} = M' \setminus K_r|_{\mathcal{D}'}$ .  $\square$

**Proposition 14** *If  $K_r$  is a removal kernel in  $M$  and  $G = AG(M)$  is an associated  $G$ -map of  $M$ , then the set  $\tilde{K}_r$  (Definition 23) is a removal kernel in  $AG(M)$ .*

*Proof:* By Theorem 4 and Proposition 8, if  $\mathcal{C}$  is a regular  $i$ -cell with local degree 2 in  $M$ , then  $\tilde{\mathcal{C}}$  is a regular  $i$ -cell with local degree 2 in  $AG(M)$ . Furthermore, since the map  $\sigma$  of Definition 7 is onto, it is readily seen that if  $\mathcal{C}_1$  and  $\mathcal{C}_2$  are two disjoint cells of  $M$ , then  $\tilde{\mathcal{C}}_1$  and  $\tilde{\mathcal{C}}_2$  are disjoint cells of  $AG(M)$ . It follows that  $\tilde{K}_r$  is a proper removal kernel in  $AG(M)$ .  $\square$

**Lemma 17** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and  $S_r = \{R_i\}_{0 \leq i \leq n}$  be a removal set in  $M$ . If  $\tilde{S}_r$  is the associated removal set of  $S_r$  in  $AG(M)$ , we have*

$$S_r = HV(\tilde{S}_r)|_{\mathcal{D}}$$

*Proof:* Let us denote  $\tilde{G} = AG(M) = (\tilde{\mathcal{D}} = \mathcal{D} \cup \mathcal{D}', \alpha_0, \dots, \alpha_n)$  following Definition 7, and  $\tilde{S}_r = \{\tilde{R}_i\}_{0 \leq i \leq n}$  the associated removal set of  $S_r$  in  $AG(M)$ .

( $\subset$ ) Let  $\mathcal{C}$  be an  $i$ -cell in  $R$  and  $b \in \mathcal{C}$ . From the very definition of the  $i$ -cell  $\tilde{\mathcal{C}}$  associated to  $\mathcal{C}$  in  $AG(M)$  and from the definition of  $\tilde{S}_r$ , we have  $b \in \tilde{\mathcal{C}} \in \tilde{R}_i$ .

Since  $b \in \tilde{R}^*$ , from Definition 22 there is a cell  $\mathcal{C}'$  in  $HV(\tilde{S}_r)$  that contains  $b$ , being a particular orbit of  $b$ . As a cell of  $HV(AG(M))$ , since  $b \in \mathcal{D}$ , the cell  $\mathcal{C}'$  belongs to  $HV(\tilde{S}_r)|_{\mathcal{D}}$ . Since  $M = HV(AG(M))|_{\mathcal{D}}$  (Proposition 4) the  $i$ -cell

$\mathcal{C}'$  is an  $i$ -cell of  $M$ . From  $b \in \mathcal{C} \cap \mathcal{C}'$  we then deduce that  $\mathcal{C} = \mathcal{C}'$  so that  $\mathcal{C}$  is an  $i$ -cell of  $HV(\tilde{S}_r)_{|\mathcal{D}}$ .  $d \in \tilde{\mathcal{C}}$

( $\supset$ ) Let  $d \in \mathcal{C}' \in HV(\tilde{S}_r)_{|\mathcal{D}}$ . From Definition 22 there exists an  $i$ -cell  $\tilde{\mathcal{C}} \in \tilde{R}$  such that  $\mathcal{C}' \subset \tilde{\mathcal{C}} \in \tilde{R}$ . The orbit  $\tilde{\mathcal{C}} \in \tilde{R}$  is a particular orbit of  $d$  in  $AG(M)$ ; in particular  $d \in \tilde{\mathcal{C}} \in \tilde{R}$ .

Following the definition of  $\tilde{S}_r$ , the cell  $\tilde{\mathcal{C}}$  is associated to an  $i$ -cell  $\mathcal{C} \in R$ . Note that, from Definition 17,  $\tilde{\mathcal{C}} \cap \mathcal{D} = \mathcal{C}$ . As  $d \in \mathcal{C}' \subset \mathcal{D}$  and  $d \in \tilde{\mathcal{C}}$  we obtain that  $d \in \mathcal{C}$ .

Finally, we have  $d \in \mathcal{C} \cap \mathcal{C}'$ . Since  $M = HV(AG(M))_{|\mathcal{D}}$  (Proposition 4) the  $i$ -cell  $\mathcal{C}'$  of  $HV(\tilde{S}_r)_{|\mathcal{D}}$  is an  $i$ -cell of  $M$ . It follows that  $\mathcal{C}'$  is an  $i$ -cell of  $R$ .  $\square$

**Theorem 6** *If  $M$  is an  $n$ -map and  $K_r$  is a removal kernel in  $M$ , the  $(n+1)$ -tuple  $M \setminus K_r$  as defined by Definition 21 is a valid  $n$ -map.*

*Proof:* With  $\tilde{G} = AG(M)$ , we have the following diagram:

$$\begin{array}{ccccc}
M & \longrightarrow & M & \xrightarrow{\text{removal of } K_r} & M \setminus K_r \\
\downarrow & & \uparrow_{|\mathcal{D}} & & \uparrow_{|\mathcal{D}} \\
AG \downarrow & & HV(\tilde{G}) & \xrightarrow{\text{removal of } HV(\tilde{K}_r)} & HV(\tilde{G}) \setminus HV(\tilde{K}_r) \\
\downarrow & & \uparrow_{HV} & & \uparrow_{HV} \\
\tilde{G} & \longrightarrow & \tilde{G} & \xrightarrow{\text{removal of } \tilde{K}_r} & \tilde{G} \setminus \tilde{K}_r
\end{array}$$

Indeed:

- We have  $HV(\tilde{G})_{|\mathcal{D}} = M$  by Proposition 4. Hence the left part of the diagram.
- If  $K_r$  is a removal kernel in  $M$ , then  $\tilde{K}_r$  as defined in Definition 24 is a removal kernel in  $\tilde{G}$  by Proposition 12. Thus the bottom-right part of the diagram holds by Proposition 11.
- We have  $K_r = HV(\tilde{K}_r)_{|\mathcal{D}}$  by Lemma 17. Thus, the upper-right part of the diagram is valid by Proposition 13.

Eventually, if we follow the path

$$M \xrightarrow{AG} \tilde{G} \xrightarrow{\setminus \tilde{K}_r} \tilde{G} \setminus \tilde{K}_r \xrightarrow{HV} HV(\tilde{G} \setminus \tilde{K}_r) \xrightarrow{|\mathcal{D}} M \setminus K_r$$

we deduce that  $M \setminus K_r$  is a valid  $n$ -map since  $\tilde{G} = AG(M)$  is an  $n$ -G-map (by Proposition 3), therefore  $\tilde{G} \setminus \tilde{K}_r$  is an  $n$ -G-map [3,4], hence  $HV(\tilde{G} \setminus \tilde{K}_r)$  is an  $n$ -map [9], and finally  $HV(\tilde{G} \setminus \tilde{K}_r)_{|\mathcal{D}}$ , that is  $M \setminus K_r$ , is an  $n$ -map following Remark 3 and Definition 8.  $\square$

**Proposition 15** *Let  $M = (\mathcal{D}, \beta_n, \dots, \beta_1)$  be an  $n$ -map and  $K_r = \{R_i\}_{0 \leq i \leq n-1}$  a removal set in  $M$ . The  $(n-1)$ -tuple obtained after removal of the cells of  $R$  is  $M' = (\mathcal{D}', \beta'_n, \dots, \beta'_1)$  defined by:*

- $\mathcal{D}' = \mathcal{D} \setminus R^*$ ;
- $\forall i \in \{1, \dots, n-1\}, \forall d \in \mathcal{D}', d\beta'_i = d\beta_1^k (\beta_i \beta_{i+1}^{-1})^{k'} \beta_i$ , where  $k$  is the smallest integer such that  $d\beta_1^k \beta_n \in \mathcal{D}'$  and  $k'$  is the smallest integer such that  $d\beta_1^{k'} (\beta_i \beta_{i+1}^{-1})^{k'} \beta_i \in \mathcal{D}'$ .
- For  $i = n, \forall d \in \mathcal{D}', d\beta'_n = d\beta_1^k \beta_n$  where  $k$  is the smallest integer such that  $d\beta'_n = d\beta_1^k \beta_n \in \mathcal{D}'$ .

*Proof:*

- For  $i \in \{1, \dots, n-2\}$  and for all  $d \in \mathcal{D}'$  we have  $d\beta'_i = d\gamma'_0 \gamma'_i$  by Proposition 2. Following Definition 21 we obtain that  $d\beta'_i = d(\gamma_0 \gamma_1)^k \gamma_0 (\gamma_i \gamma_{i+1})^h \gamma_i$  where  $k$  is the smallest integer such that  $d(\gamma_0 \gamma_1)^k \gamma_0 \in \mathcal{D}'$  (i.e. such that  $d\beta_1^k \beta_n \in \mathcal{D}'$  since  $\gamma_0 \gamma_1 = \beta_1$  and  $\gamma_0 = \beta_n$ ), and  $h$  is the smallest integer such that  $d(\gamma_0 \gamma_1)^k \gamma_0 (\gamma_i \gamma_{i+1})^h \gamma_i \in \mathcal{D}'$ .

We may thus rewrite,

$$\begin{aligned} d\beta'_i &= d(\gamma_0 \gamma_1)^k \gamma_0 (\gamma_i \gamma_{i+1} \gamma_0 \gamma_0)^h \gamma_i \\ &= d(\gamma_0 \gamma_1)^k (\gamma_0 \gamma_i \gamma_{i+1} \gamma_0)^h \gamma_0 \gamma_i \\ &= d\beta_1^k (\beta_i \beta_{i+1}^{-1})^h \beta_i \end{aligned} \quad \begin{aligned} &(\gamma_0 \gamma_1 = \beta_1 \text{ and for all } i \in \{1, \dots, n-2\}, \\ &\gamma_0 \gamma_i = \beta_i \text{ and } \gamma_{i+1} \gamma_0 = \beta_{i+1}^{-1}) \end{aligned}$$

- For  $i = n-1$ , we have

$$\begin{aligned} d\beta'_{n-1} &= d\gamma'_0 \gamma'_{n-1} && \text{(Proposition 2)} \\ &= d(\gamma_0 \gamma_1)^k \gamma_0 \gamma_{n-1}^{h+1} && \text{(Definition 21)} \\ &= d\beta_1^k \beta_n (\beta_n \beta_{n-1})^{h+1} && \text{(Proposition 2)} \\ &= d\beta_1^k (\beta_{n-1} \beta_n)^h \beta_{n-1} && ((\beta_n \beta_{n-1})^{h+1} = \beta_n (\beta_{n-1} \beta_n)^h \beta_{n-1}) \\ &= d\beta_1^k (\beta_{n-1} \beta_n^{-1})^h \beta_{n-1} && (\beta_n = \beta_n^{-1}) \end{aligned}$$

where  $k$  is the smallest integer such that  $d(\gamma_0 \gamma_1)^k \gamma_0 = d\beta_1^k \beta_n \in \mathcal{D}'$  and  $h$  is the smallest integer such that  $d\beta_1^k (\beta_{n-1} \beta_n^{-1})^h \beta_{n-1} \in \mathcal{D}'$ .

- For  $i = n$ , from Proposition 2 we have  $\beta'_n = \gamma'_0$ . By Definition 21 we know that for all  $d \in \mathcal{D}'$ ,  $d\beta'_n = d(\gamma_0 \gamma_1^{-1})^k \gamma_0$  where  $k$  is the smallest integer such that  $d(\gamma_0 \gamma_1^{-1})^k \gamma_0 \in \mathcal{D}'$ . We may rewrite  $d\beta'_n = d\gamma_0 (\gamma_1^{-1} \gamma_0)^k$ . From Proposition 2,  $\gamma_0 = \beta_n$  and  $\gamma_1^{-1} \gamma_0 = \beta_1^{-1}$ , therefore  $d\beta'_n = d\beta_n \beta_1^{-k}$ . Since  $\beta'_n$  is an involution,  $d\beta'_n = d\beta_n^{-1} = d\beta_1^k \beta_n^{-1}$ . Again,  $\beta_n = \beta_n^{-1}$  so that  $d\beta'_n = d\beta_1^k \beta_n$ .

□



### 3.2 Cells contraction

**Definition 26 (Contraction kernel)** Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ - $G$ -map and  $K_c = \{C_i\}_{0 \leq i \leq n}$  be sets of  $i$ -cells with  $C_0 = \emptyset$ . Let  $C = \cup_{i=0}^n C_i$ . Furthermore, we suppose that the cells of  $C$  are disjoint (i.e.  $\forall c, c' \in C, c \cap c' = \emptyset$ ), have a dual local degree 2, and are regular cells in  $\overline{G}$ . The family of sets  $K_c$  is then called a contraction kernel in  $G$ .

We also denote:

$$C_i^* = \bigcup_{c \in C_i} c \text{ and } C^* = \bigcup_{i \in \{0, \dots, n\}} C_i^*$$

A contraction kernel is defined in a similar way for an  $n$ -map  $M$ .

**Remark 7** If  $G$  is an  $n$ - $G$ -map, then from the very definition of cells (Definition 9) an  $i$ -cell in  $G$  is an  $(n - i)$ -cell in  $\overline{G}$ .

**Proposition 16** If  $G$  is an  $n$ - $G$ -map, a contraction kernel  $K_c$  in  $G$  is a removal kernel in  $\overline{G}$ .

*Proof:* If  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  we may write  $\overline{G} = (\mathcal{D}, \overline{\alpha}_0, \dots, \overline{\alpha}_n)$  with  $\overline{\alpha}_i = \alpha_{n-i}$  for all  $i \in \{0, \dots, n\}$ . Thus, for any dart  $d \in \mathcal{D}$  and any  $i \in \{0, \dots, n\}$  we have  $\mathcal{C}_i(d) = \langle \alpha_0, \dots, \hat{\alpha}_i, \dots, \alpha_n \rangle(d) = \langle \overline{\alpha}_n, \dots, \hat{\overline{\alpha}}_{n-i}, \dots, \overline{\alpha}_0 \rangle(d)$ .

It follows that the set of  $n$ -cells of  $K_c$  in  $G$ , which is empty, is precisely a set of 0-cells in  $\overline{G}$ .

From Definitions 9, 12, and 6 it is also readily seen that an  $i$ -cell of degree 2 in  $G$  is an  $(n - i)$ -cell of dual degree 2 in  $\overline{G}$ . Eventually, from Definition 26 a cell of  $K_c$  is a regular cell of  $\overline{G}$ .  $\square$

The following definition is adapted from [6] where a definition combining removals and contractions was given. The definition below is obtained by considering that no cell is to be removed.

The operation of cells contraction in  $n$ - $G$ -maps is defined as follows in [6]

**Note 2 (Definition of cells contraction by [6])** Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ - $G$ -map and  $K_c = \{C_i\}_{1 \leq i \leq n}$  a contraction kernel in  $G$ . Let  $BV_i = C_i^* \alpha_i \setminus C_i^*$ ,  $\forall i, 0 \leq i \leq n$ . The set  $BV_i$  is called the set of surviving darts which are neighbors of an  $i$ -cell to be contracted. The  $n$ - $G$ -map resulting of the contraction of the cells of  $C$  is  $G' = (\mathcal{D}', \alpha'_0, \dots, \alpha'_n)$  defined by:

- (1)  $\mathcal{D}' = \mathcal{D} \setminus C^*$ ;
- (2)  $\forall i, 0 \leq i \leq n, \forall b \in \mathcal{D}' \setminus BV_i, b\alpha'_i = b\alpha_i$ ;

- (3)  $\forall i, 0 < i \leq n, \forall b \in \text{BV}_i, b\alpha'_i = b' = b(\alpha_i\alpha_{i-1})^k\alpha_i$  where  $k$  is the smallest integer such that  $b' \in \text{BV}_i$ .

In this paper, we choose to define the contraction operation in G-maps as a removal operation in the dual map (Definition 27 below). The equivalence between this definition and the one (Note 2) given by Grasset in [6] or by Damiand and Lienhardt in [3] will be stated by Proposition 19.

**Definition 27 (Cells contraction in  $n$ -G-maps)** *Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ -G-map and  $K_c = \{C_i\}_{1 \leq i \leq n}$  be a contraction kernel. The  $n$ -G-map resulting of the contraction of the cells of  $K_c$  is  $G' = \overline{G} \setminus K_c$ .*

**Notation 5** *The  $n$ -G-map obtained after the contraction of a kernel  $K_c = \{C_i\}_{0 \leq i \leq n}$  from an  $n$ -G-map  $G$  will be denoted either by  $G/K_c$ , or by  $G/C^*$ .*

**Proposition 17** *Let  $G, G'$  be  $n$ -G-maps and  $K_c = \{C_i\}_{0 \leq i \leq n}$  be a contraction kernel as in Definition 27. Since  $C_0 = \emptyset$ , then  $d\alpha_0 \in \mathcal{D}'$  for all  $d \in \mathcal{D}'$ .*

*Proof:* It is readily seen that  $d\alpha_0 \in \mathcal{D}'$  for all  $d \in \mathcal{D}'$ . Indeed, suppose that  $d\alpha_0 \in \mathcal{C}_i \in C_i$  for some  $i \in \{1, \dots, n\}$ . In other words,  $d\alpha_0$  belongs to an  $i$ -cell which is to be removed for  $i > 0$ . Since  $i > 0$ , the orbit that defines  $\mathcal{C}_i$  obviously contains  $b\alpha_0$  for all  $b \in \mathcal{C}_i$  (Definition 9). Therefore,  $d\alpha_0\alpha_0 = d$  also belongs to  $\mathcal{C}_i$ . This is a contradiction with the fact that  $d \in \mathcal{D}'$ .  $\square$

**Proposition 18** *Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ -G-map and  $K_c = \{C_i\}_{1 \leq i \leq n}$  be a contraction kernel. The  $n$ -G-map resulting of the contraction of the cells of  $C$  according to Definition 27 is  $G' = (\mathcal{D}', \alpha'_0, \dots, \alpha'_n)$  defined by:*

- (1)  $\mathcal{D}' = \mathcal{D} \setminus C$ ;
- (2)  $\forall d \in \mathcal{D}', d\alpha'_0 = d\alpha_0$ ;
- (3)  $\forall i, 0 < i \leq n, \forall d \in \mathcal{D}', d\alpha'_i = d' = d(\alpha_i\alpha_{i-1})^k\alpha_i$  where  $k$  is the smallest integer such that  $d' \in \mathcal{D}'$ .

*Proof:* Let  $\overline{G} = (\mathcal{D}, \overline{\alpha}_0, \dots, \overline{\alpha}_n)$  with  $\overline{\alpha}_i = \alpha_{n-i}$  for  $0 \leq i \leq n$ . From Proposition 16,  $K_c$  is a removal kernel in  $\overline{G}$  and we denote  $G'' = \overline{G} \setminus K_c$ . Thus, from Definition 20  $G'' = (\mathcal{D}'', \overline{\alpha}''_0, \dots, \overline{\alpha}''_n)$  where:

- $\mathcal{D}'' = \mathcal{D} \setminus C$ ;
- $\forall d \in \mathcal{D}'', d\overline{\alpha}''_n = d\overline{\alpha}_n$ ;
- $\forall i, 0 \leq i < n, \forall d \in \mathcal{D}'', d\overline{\alpha}''_i = d' = (\overline{\alpha}_i\overline{\alpha}_{i+1})^k\overline{\alpha}_i$  where  $k$  is the smallest integer such that  $d' \in \mathcal{D}''$ .

Now, let us denote  $G/K_c = G' = (\mathcal{D}', \alpha'_0, \dots, \alpha'_n)$  following Definition 27. Since  $G' = \overline{G}''$  we have  $\alpha'_i = \overline{\alpha}''_{n-i}$  for  $0 \leq i \leq n$ . Therefore, we obtain:

- $\forall d \in \mathcal{D}', d\alpha'_0 = d\overline{\alpha}''_n = d\overline{\alpha}_n$ ;

- $\forall i, 0 < i \leq n, \forall d \in \mathcal{D}', d\alpha'_i = d\bar{\alpha}''_{n-i} = d' = d(\bar{\alpha}_{n-i}\bar{\alpha}_{n-(i-1)})^k\bar{\alpha}_{n-i}$  where  $k$  is the smallest integer such that  $d' \in \mathcal{D}''$ .

or again, since  $\alpha_i = \bar{\alpha}_{n-i}$  for  $0 \leq i \leq n$ ,

- $\forall d \in \mathcal{D}', d\alpha'_0 = \alpha_0$ ;
- $\forall i, 0 < i \leq n, \forall d \in \mathcal{D}', d\alpha'_i = d\bar{\alpha}''_{n-i} = d' = d(\alpha_i\alpha_{i-1})^k\alpha_i$  where  $k$  is the smallest integer such that  $d' \in \mathcal{D}''$ .

Which is precisely the definition of  $\alpha'_i$  for  $0 \leq i \leq n$  in Proposition 18.  $\square$

**Proposition 19** *Definition 27 and the one given by Grasset (Note 2, see also [6]) are equivalent.*

*Proof:* Let  $G = (\mathcal{D}, \alpha_0, \dots, \alpha_n)$  be an  $n$ -G-map and  $K_c = \{C_i\}_{1 \leq i \leq n}$  a contraction kernel in  $G$ .

We first express  $G/K_c = \overline{G \setminus K_c}$ , following Definition 27. Thus, let us write  $\overline{G} = (\mathcal{D}, \bar{\alpha}_0, \dots, \bar{\alpha}_n)$  where  $\bar{\alpha}_i = \alpha_{n-i}$  for  $0 \leq i \leq n$ . From Proposition 16,  $K_c$  is a removal kernel in  $\overline{G}$  which contains no  $n$ -cell of  $\overline{G}$ . Then, let  $\overline{G}' = \overline{G} \setminus K_c = (\mathcal{D}', \bar{\alpha}'_0, \dots, \bar{\alpha}'_n)$  be the map obtained after removal of  $K_c$  from  $\overline{G}$ . From [6, Definition 10] (see also Note 1) and by Proposition 10,  $\overline{G}'$  is defined by:

- (1)  $\mathcal{D}' = \mathcal{D} \setminus C^*$ ;
- (2)  $\forall i, 0 \leq i \leq n, \forall b \in \mathcal{D}' \setminus BV_i, b\bar{\alpha}'_i = b\bar{\alpha}_i$ ;
- (3)  $\forall i, 0 \leq i < n, \forall b \in BV_i, b\bar{\alpha}'_i = b' = b(\bar{\alpha}_i\bar{\alpha}_{i+1})^k\bar{\alpha}_i$  where  $k$  is the smallest integer such that  $b' \in BV_i$ .

Now, let  $G'' = G/K_c = \overline{G' \setminus K_c} = \overline{G'}$ . We denote  $G'' = (\mathcal{D}', \alpha''_0, \dots, \alpha''_n)$  with  $\alpha''_i = \bar{\alpha}'_{n-i}$  for all  $i \in \{0, \dots, n\}$ . From the above definition of  $\bar{\alpha}'_i$ ,  $0 \leq i \leq n$  we obtain:

- (1)  $\mathcal{D}' = \mathcal{D} \setminus C^*$ ;
- (2)  $\forall i, 0 \leq i \leq n, \forall b \in \mathcal{D}' \setminus BV_i, b\alpha''_i = b\bar{\alpha}_{n-i}$ ;
- (3)  $\forall i, 0 < i \leq n, \forall b \in BV_i, b\alpha''_i = b' = b(\bar{\alpha}_{n-i}\bar{\alpha}_{(n-i)+1})^k\bar{\alpha}_{n-i}$  where  $k$  is the smallest integer such that  $b' \in BV_i$ .

Using the relation  $\bar{\alpha}_{n-i} = \alpha_i$  for  $0 \leq i \leq n$ , we deduce:

- (1)  $\mathcal{D}' = \mathcal{D} \setminus C^*$ ;
- (2)  $\forall i, 0 \leq i \leq n, \forall b \in \mathcal{D}' \setminus BV_i, b\alpha''_i = b\alpha_i$ ;
- (3)  $\forall i, 0 < i \leq n, \forall b \in BV_i, b\alpha''_i = b' = b(\alpha_i\alpha_{i-1})^k\alpha_i$  where  $k$  is the smallest integer such that  $b' \in BV_i$ .

This definition of  $\alpha_i''$  for  $0 \leq i \leq n$  is precisely the one given by Note 2 for the  $n$ -G-map obtained after contraction of  $K_c$  from  $G$ .  $\square$

**Definition 28 (Cells contraction in  $n$ -maps)** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map and let  $K_c = \{C_i\}_{1 \leq i \leq n}$  be a contraction kernel. The  $n$ -map resulting of the contraction of the cells of  $K_c$ , which we denote  $M/K_c$  is the  $n$ -map  $\overline{M} \setminus K_c$ .*

The following proposition provides the justification for the definition of cells contraction in  $n$ -maps.

**Proposition 20** *We have the following commutative diagram:*

$$\begin{array}{ccc} G & \xrightarrow{\text{contraction of } K_c} & G' = G/K_c \\ HV \downarrow & & HV \downarrow \\ M & \xrightarrow{\text{contraction of } HV(K_c)} & M' = M/K_c \end{array}$$

*Proof:* The diagram is a consequence of the one below, which comes from Proposition 1, Proposition 11 and Definition 27.

$$\begin{array}{ccccccc} G & \xrightarrow{\text{dual}} & \overline{G} & \xrightarrow{\text{removal of } K_c} & \overline{G} \setminus K_c & \xrightarrow{\text{dual}} & \overline{\overline{G} \setminus K_c} = \overline{\overline{G}}/K_c = G/K_c \\ HV \downarrow & & HV \downarrow & & HV \downarrow & & HV \downarrow \\ M & \xrightarrow{\text{dual}} & \overline{M} & \xrightarrow{\text{removal of } HV(K_c)} & \overline{M} \setminus K_c & \xrightarrow{\text{dual}} & \overline{\overline{M} \setminus K_c} = \overline{\overline{M}}/K_c = M/K_c \\ & (1) & & (2) & & (3) & \end{array}$$

Indeed, parts (1) and (3) of the above diagram were stated by Proposition 1. Part (2) is precisely the diagram of Proposition 11. Eventually, the equalities  $\overline{\overline{G} \setminus K_c} = \overline{\overline{G}}/K_c$  and  $\overline{\overline{M} \setminus K_c} = \overline{\overline{M}}/K_c$  follow Definition 27.  $\square$

**Proposition 21** *Let  $M = (\mathcal{D}, \gamma_0, \dots, \gamma_{n-1})$  be an  $n$ -map. Let  $K_c = \{C_i\}_{1 \leq i \leq n}$  be a contraction kernel. The  $n$ -map obtained after contraction of the cells of  $K_c$ ,  $M' = (\mathcal{D}', \gamma'_0, \dots, \gamma'_{n-1})$  is defined by:*

- $\mathcal{D}' = \mathcal{D} \setminus C;$
- $\forall d \in \mathcal{D}', d\gamma'_0 = d\gamma_{n-1}^k \gamma_0$  where  $k$  is the smallest integer such that  $d\gamma_{n-1}^k \gamma_0 \in \mathcal{D}'$ ;
- $\forall i \in \{1, \dots, n-1\}, \forall d \in \mathcal{D}', d\gamma'_i = d\gamma_{n-1}^k (\gamma_i \gamma_{i-1}^{-1})^{k'} \gamma_i$ , where  $k$  is the smallest integer such that  $d\gamma_{n-1}^k \in \mathcal{D}'$  and  $k'$  is the smallest integer such that  $d\gamma_{n-1}^k (\gamma_i \gamma_{i-1}^{-1})^{k'} \gamma_i \in \mathcal{D}'$ .

*Proof:* The  $n$ -map obtained after the contraction of the cells in  $K_c$  in  $M$  is  $M' = \overline{M} \setminus K_c$ .

Let  $\overline{M} = (\mathcal{D}, \overline{\gamma}_0 = \gamma_0^{-1}, \overline{\gamma}_1 = \gamma_0^{-1}\gamma_{n-1}, \dots, \overline{\gamma}_{n-1} = \gamma_0^{-1}\gamma_1)$  (Definition 6) and let  $M'' = \overline{M} \setminus K_c$ , if we denote  $M'' = (\mathcal{D}', \gamma''_0, \dots, \gamma''_{n-1})$ , according to Definition 21 and the above notations we have:

- $\mathcal{D}' = \mathcal{D} \setminus R^*$ ;
- $\forall i \in \{0, \dots, n-2\}, \forall d \in \mathcal{D}', d\gamma''_i = d(\overline{\gamma}_i \overline{\gamma}_{i+1}^{-1})^k \overline{\gamma}_i$ , where  $k$  is the smallest integer such that  $d(\overline{\gamma}_i \overline{\gamma}_{i+1}^{-1})^k \overline{\gamma}_i \in \mathcal{D}'$ .
- For  $i = n-1, \forall d \in \mathcal{D}', d\gamma''_{n-1} = d\overline{\gamma}_{n-1}^{k+1}$  where  $k$  is the smallest integer such that  $d\overline{\gamma}_{n-1}^{k+1} \in \mathcal{D}'$ .

Since  $M' = \overline{M''}$ , by Definition 6 we have

$$M' = (\mathcal{D}', \gamma'_0 = \gamma''_0, \gamma'_1 = \gamma''_0 \gamma''_{n-1}, \dots, \gamma'_{n-1} = \gamma''_0 \gamma''_1)$$

Thus,

- For  $i = 0, d\gamma'_0 = d\gamma''_0 = d(\overline{\gamma}_0 \overline{\gamma}_1^{-1})^k \overline{\gamma}_0 = d(\gamma_0^{-1} \gamma_{n-1}^{-1} \gamma_0)^k \gamma_0^{-1} = d\gamma_0^{-1} \gamma_{n-1}^{-k}$ . Since  $\gamma'_0$  is an involution, we have

$$d\gamma'_0 = d\gamma'_{0^{-1}} = d(\gamma_0^{-1} \gamma_{n-1}^{-k})^{-1} = d\gamma_{n-1}^k \gamma_0 \quad (7)$$

- For  $i = 1,$

$$\begin{aligned} d\gamma'_1 &= d\gamma''_0 \gamma''_{n-1} = d\gamma_{n-1}^k \gamma_0 \overline{\gamma}_{n-1}^{h+1} && \text{(from (7))} \\ &= d\gamma_{n-1}^k \gamma_0 (\gamma_0^{-1} \gamma_1)^{h+1} \\ &= d\gamma_{n-1}^k \gamma_0 \gamma_0^{-1} (\gamma_1 \gamma_0^{-1})^h \gamma_1 \\ &= d\gamma_{n-1}^k (\gamma_1 \gamma_0^{-1})^h \gamma_1 \end{aligned}$$

- For  $i \in \{2, \dots, n-1\},$

$$\begin{aligned} d\gamma'_i &= d\gamma''_0 \gamma''_{n-i} = d\gamma_{n-1}^k \gamma_0 (\overline{\gamma}_{n-i} \overline{\gamma}_{(n-i)+1}^{-1})^h \overline{\gamma}_{n-i} \\ &= d\gamma_{n-1}^k \gamma_0 (\gamma_0^{-1} \gamma_i \gamma_{i-1}^{-1} \gamma_0)^h \gamma_0^{-1} \gamma_i \\ &= d\gamma_{n-1}^k \gamma_0 \gamma_0^{-1} (\gamma_i \gamma_{i-1}^{-1})^h \gamma_i \\ &= d\gamma_{n-1}^k (\gamma_i \gamma_{i-1}^{-1})^h \gamma_i \end{aligned}$$

□

**Proposition 22** *Let  $M = (\mathcal{D}, \beta_1, \dots, \beta_n)$  be an  $n$ -map. Let  $K_c = \{C_i\}_{1 \leq i \leq n}$  be a contraction kernel. The  $n$ -map obtained after contraction of the cells of  $K_c$ ,  $M' = (\mathcal{D}', \beta'_1, \dots, \beta'_n)$  is equivalently defined by:*

- $\mathcal{D}' = \mathcal{D} \setminus C$ ;
- For  $i = 1, \forall d \in \mathcal{D}'$ ,  $d\beta'_1 = d\beta_1^{k+1}$ , where  $k$  is the smallest integer such that  $d\beta_1^{k+1} \in \mathcal{D}'$ .
- $\forall i \in \{2, \dots, n\}, \forall d \in \mathcal{D}'$ ,  $d\beta'_i = d(\beta_i\beta_{i-1}^{-1})^k\beta_i$ , where  $k$  is the smallest integer such that  $d(\beta_i\beta_{i-1}^{-1})^k\beta_i \in \mathcal{D}'$ .

*Proof:* We use the definition of the contraction in  $M$  as a removal of  $K_c$  in the dual map  $\overline{M}$ . Following Proposition 2, we will denote

$$M_1 = \overline{M} = (\mathcal{D}, \beta_n \stackrel{\text{not.}}{=} \overline{\gamma_0}, \dots, \beta_1 \stackrel{\text{not.}}{=} \overline{\gamma_{n-1}}) \quad (8)$$

From Definition 28,  $M' = M/K_c = \overline{\overline{M} \setminus K_c}$ . Let  $M'_1 = \overline{M} \setminus K_c = (\mathcal{D}, \overline{\gamma}'_0, \dots, \overline{\gamma}'_{n-1})$ . From Definition 21, the involutions  $\overline{\gamma}'_i$  are defined by

- $d\overline{\gamma}'_i = d(\overline{\gamma}_i\overline{\gamma}_{i+1}^{-1})^k\overline{\gamma}_i$  for  $i \in \{0, \dots, n-2\}$ , and
- $d\overline{\gamma}'_{n-1} = d\overline{\gamma}_{n-1}^{k+1}$  if  $i = n-1$ .

With the notations of Proposition 2 we obtain:

- $d\beta'_{(n-i)} = d(\beta_{(n-i)}\beta_{(n-i)-1}^{-1})^k\beta_{(n-i)}$  for  $i \in \{0, \dots, n-2\}$ , and
- $d\beta'_1 = d\beta_1^{k+1}$  if  $i = 1$ .

where  $(n-i) \in \{2, \dots, n\}$  when  $i \in \{0, \dots, n-2\}$ .  $\square$

## 4 Conclusion and perspectives

We have defined cells removal and contraction in combinatorial maps, based on the previous work by Damiand and Lienhardt for generalized maps.

A logical sequel of this paper will be the definition of  $n$ -dimensional combinatorial pyramids and the related notions, the way Brun and Kropatch [1] did in the two-dimensional case and following the works of Grasset [6] about pyramids of generalized maps.



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