Ideas from Zariski topology in the study of cubical sets, cubical maps, and their homology

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January 24, 2005

Abstract

Cubical sets and their homology have been used in dynamical systems as well as in digital imaging. We take a refreshing view on this topic, following Zariski ideas from algebraic geometry. The cubical topology is defined to be a topology in $\mathbb{R}^d$ in which a set is closed if and only if it is cubical. This concept is a convenient frame for describing a variety of important features of cubical sets. Separation axioms which, in general, are not satisfied here, characterize exactly those pairs of points which we want to distinguish. The noetherian property guarantees the convergence of algorithms. Moreover, maps between cubical sets which are continuous and closed with respect to the cubical topology are precisely those for whom the homology map can be defined and computed without grid subdivisions. A combinatorial version of the Vietoris-Begle is derived and used for an algorithm computing homology of maps which are continuous with respect to the Euclidean topology.

*Research supported by a grant from NSERC
†Research supported by Polish KBN grant no. 2 P03A 041 24
[0]2000 Mathematics Subject Classification: Primary 55-04; Secondary 52B05, 54C60, 68W05, 68W30, 68U10.

1 Introduction

Representable sets, in particular, cubical sets, and their homology have proved to be useful geometric structures in a variety of applications from the Conley index in dynamical systems [8, 12, 15, 16] to image and pattern recognition in digital imaging [2, 3, 8]. We take a new refreshing view on this topic, following Zariski ideas from algebraic geometry. Recall from [4, 7] that the *Zariski topology* in the Euclidean space $\mathbb{R}^d$ is defined by declaring that a proper subset of $\mathbb{R}^d$ is *closed* if and only if it is algebraic. The *cubical topology* is a topology in $\mathbb{R}^d$ in which a proper subset is closed if and only if it is cubical.

It seems foolish at first to abandon the standard Euclidean topology and introduce one which is not metrizable — more than that — which does not satisfy any separation axiom! Nevertheless, the points which we want to distinguish in a cubical set are exactly those which belong to different cells or different elementary cubes, thus, the points separated by the cubical topology. In digital imaging, computer scientists seem to have a hard time deciding if they prefer to interpret pixels as unit size squares or as isolated points in a square grid. The cubical topology permits these two interpretations co-exist on mathematical grounds.

Cubical topology has some more interesting features. A crucial property of the Zariski topology, related to the Hilbert Nullstellensatz is that it is *noetherian*, that is, every decreasing sequence of closed sets eventually becomes constant. That the cubical topology is noetherian is quite obvious but the simplicity of this observation does not diminish its importance: In fact, all algorithms constructing isolating neighborhoods and index pairs in dynamics are based on this property. Also, *irreducible* closed sets are precisely elementary cubes. Moreover, maps $f : X \to Y$ between cubical sets which are continuous and closed with respect to the cubical topology are precisely those for whom the homology map $H_*(f)$ can be defined and computed without grid rescaling (the concept of rescaling is defined in [8]) or, equivalently, without grid subdivisions. Although this class of maps, called cubical maps, seems somewhat restrictive, its study leads to algorithms for constructing homology of maps which are continuous with respect to the Euclidean topology.

This paper is organized as follows. In Section 2, definitions and properties of cubical sets, cubical chain complex, and representable sets are recalled from [8]. Note that the cubical chain complex studied here is a combinatorial concept in contrast with a well known but less suitable for algorithms concept of *singular cubical complex* presented for instance in [9]. In Sec-

tion 3, definition and properties of cubical topology are presented. For some routine proofs we refer to [17]. In Section 4, we define the class of cubical maps as the class of maps on cubical sets which are continuous and closed with respect to the relative cubical topology. We discuss the relation of this definition to the one given in [5], and give an explicit formula for a cubical map in terms of it's coordinate functions. Using that formula, the homomorphism induced in homology by a cubical map is constructed. In Section 4.3 a combinatorial version of the Vietoris-Begle Theorem (see, e.g. [6] for one of classical formulations) is derived for cubical maps. In Section 5, we show how that result is used for constructing the homology of maps on cubical sets which are continuous in Euclidean topology. The construction is based on ideas from [6] and [1], and it has been implemented in [10]. The related algorithm is presented in Section 6.

2 Preliminaries

We recall here from [8] basic terminology related to cubical sets, cubical chain complex, and representable sets. The proofs of all statements of this section can be found in [8] except for Proposition 2.1 which is proved in [17].

2.1 Cubical Sets

An *elementary cube* is a finite product of intervals

$$Q = I_1 \times I_2 \times \ldots \times I_d \subset \mathbb{R}^d, \tag{1}$$

where I_i is either a unit interval $[l_i, l_i + 1]$ or a point (*degenerated interval*) $[l_i, l_i] = [l_i] := \{l_i\}$, and $l_i \in \mathbb{Z}$, $\mathbb{Z}$ the set of all integers. The set of all elementary cubes is denoted by $\mathcal{K}$ and the set of those which are in $\mathbb{R}^d$ for a specific d is denoted by $\mathcal{K}^d$. The number d in (1) is called the *embedding number* of Q and is denoted by $\operatorname{emb} Q$. The *dimension* of Q is the number of non-degenerated intervals I_i of the form $[l_i, l_i + 1]$ in (1) is called the *dimension* and is denoted by $\dim Q$. We put

$$\mathcal{K}_k := \{Q \in \mathcal{K} \mid \dim Q = k\}$$

and

$$\mathcal{K}^d_k := \mathcal{K}^d \cap \mathcal{K}_k.$$

Let $Q, P \in \mathcal{K}$. If $Q \subset P$, then Q is a *face* of P. If $Q \subset P$ and $Q \neq P$, then Q is a *proper face* of P.

Proposition 2.1 *Let $Q \in \mathcal{K}_k^d$, then Q has 3^k faces.*

A set $X \subset \mathbb{R}^d$ is *cubical* if X can be written as a finite union of elementary cubes.

Given a cubical set $X \subset \mathbb{R}^d$, we denote by $\mathcal{K}(X)$, respectively $\mathcal{K}_k(X)$, the set of those $Q \in \mathcal{K}^d$, respectively in $Q \in \mathcal{K}_k^d$, that $Q \subset X$. If $Q \in \mathcal{K}(X)$ is not a proper face of some $P \in \mathcal{K}(X)$, then it is called a *maximal face* in X. The set of maximal faces in X is denoted by $\mathcal{K}_{\max}(X)$.

2.2 Cubical Chain Complex

The group C_k^d of *k-dimensional chains* of $\mathbb{R}^d$ (k-chains for short) is the free abelian group generated by $\mathcal{K}_k^d$. By definition, the elements of C_k^d are functions $c : \mathcal{K}_k^d \to \mathbb{Z}$ such that $c(Q) = 0$ for all but a finite number of $Q \in \mathcal{K}_k^d$. We distinguish between the geometric objects, elementary cubes $Q \in \mathcal{K}_k^d$, and the corresponding algebraic objects, their *duals* $\widehat{Q} : \mathcal{K}_k^d \to \mathbb{Z}$, defined on any $P \in \mathcal{K}^d$ by

$$\widehat{Q}(P) := \begin{cases} 1 & \text{if } P = Q, \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

The set $\{\widehat{Q} \mid Q \in \mathcal{K}_k^d\}$ is the *canonical basis* for C_k^d.

We put $C_k^d = 0$ if $k > d$, $k < 0$, or $d < 0$. In order to define the chain complex structure for the collection of groups $\{C_k^d\}_{k \in \mathbb{Z}}$, we first need the following auxiliary operation.

Given $P \in \mathcal{K}_k^d$ and $Q \in \mathcal{K}_{k'}^{d'}$, we have $P \times Q \in \mathcal{K}_{k+k'}^{d+d'}$. Set

$$\widehat{P} \diamond \widehat{Q} := \widehat{P \times Q}.$$

This definition extends to arbitrary chains $c_1 \in C_k^d$ and $c_2 \in C_{k'}^{d'}$ by

$$c_1 \diamond c_2 := \sum_{P \in \mathcal{K}_k, Q \in \mathcal{K}_{k'}} c_1(P) c_2(Q) \widehat{P \times Q}.$$

The chain $c_1 \diamond c_2 \in C_{k+k'}^{d+d'}$ is called the *cubical product* of c_1 and c_2.

Given $k \in \mathbb{Z}$, the *cubical boundary map*

$$\partial_k : C_k^d \to C_{k-1}^d$$

is a homomorphism defined on generators $\widehat{Q}$, where $Q \in \mathcal{K}_k^d$, by induction on the embedding number d as follows.

Let first $d = 1$. Then $Q = [l] \in \mathcal{K}_0^1$ or $Q = [l, l+1] \in \mathcal{K}_1^1$ for some $l \in \mathbb{Z}$. Define

$$\partial_k \widehat{Q} := \begin{cases} 0 & \text{if Q=[l],} \\ \widehat{[l+1]} - \widehat{[l]} & \text{if } Q = [l, l+1]. \end{cases}$$

Let $d > 1$ and $Q = \prod_{i=1}^d I_i$, where I_i are intervals (some possibly degenerated) in $\mathbb{R}$. Put $I = I_1$ and $P = \prod_{i=2}^d I_i$. Then $\widehat{Q} = \widehat{I} \diamond \widehat{P}$. Define

$$\partial_k \widehat{Q} := \partial_{k_1} \widehat{I} \diamond \widehat{P} + (-1)^{\dim I} \widehat{I} \diamond \partial_{k_2} \widehat{P}, \tag{3}$$

where $k_1 = \dim I$ and $k_2 = \dim P$. Finally, we extend the definition to all chains by linearity. It is shown in [8] that cubical boundary maps satisfy the algebraic condition for a boundary map in an arbitrary chain complex, that is,

$$\partial_k \circ \partial_{k+1} = 0, \tag{4}$$

for all $k \in \mathbb{Z}$. Thus $\mathcal{C} := \{C_k, \partial_k\}_{k \in \mathbb{Z}}$ is a chain complex. We shall now localize this chain complex to cubical sets. The *support* of a chain $c \in C_k^d$ is the cubical set

$$|c| := \bigcup \left\{ Q \in \mathcal{K}_k^d \mid c(Q) \neq 0 \right\}.$$

Given a cubical set $X \subset \mathbb{R}^d$, we define

$$C_k(X) = \left\{ c \in C_k^d \mid |c| \subset X \right\}. \tag{5}$$

$C_k(X)$ is a finitely generated free abelian group and the set $\{\widehat{Q} \mid Q \in \mathcal{K}_k(X)\}$ is its basis called *canonical basis*. We also have

$$\partial_k(C_k(X)) \subset C_{k-1}(X).$$

Hence, the restricted boundary map $\partial_k^X : C_k(X) \to C_{k-1}(X)$ is well defined and

$$\mathcal{C}(X) := \left\{ C_k(X), \partial_k^X \right\}_{k \in \mathbb{Z}},$$

is a chain complex called *cubical chain complex* of X. When X it is clear from the context, we will use the notation ∂_k for the restricted map ∂_k^X.

The *homology* of X is the collection $H_*(X) = \{H_k(X)\}_{k \in \mathbb{Z}}$ of quotient groups

$$H_k(X) := Z_k(X)/B_k(X),$$

where $Z_k(X) := \ker \partial_k^X$ is the group of k-*cycles* of X and $B_k(X) := \operatorname{im} \partial_{k+1}^X$ is the group of k-*boundaries* of X.

2.3 Representable Sets

Note that any cubical set $X \subset \mathbb{R}^d$ is closed and bounded. Intersections and finite unions of cubical sets are cubical. We want to obtain a larger class of sets, closed under the substraction $X \setminus Y$.

Given any elementary cube $Q = I_1 \times I_2 \times \ldots \times I_d$, the corresponding *elementary cell*

$$\overset{\circ}{Q} = \overset{\circ}{I}_1 \times \overset{\circ}{I}_2 \times \ldots \times \overset{\circ}{I}_d$$

is the set obtained by replacing all non-degenerated closed intervals $I_i = [l_i, l_i + 1]$ in the expression for Q by the open ones $\overset{\circ}{I}_i = (l_i, l_i + 1)$, while $\overset{\circ}{I}_i := I_i$ if $I_i = [l_i]$.

Proposition 2.2 *Elementary cells have the following properties:*

(i) $\mathbb{R}^d = \bigcup\{\overset{\circ}{Q} \mid Q \in \mathcal{K}^d\}$.

(ii) If $A \subset \mathbb{R}^d$ is bounded then the set $\{Q \in \mathcal{K}^d \mid \overset{\circ}{Q} \cap A \neq \emptyset\}$ is finite.

(iii) If $P, Q \in \mathcal{K}^d$, then $\overset{\circ}{P} \cap \overset{\circ}{Q} = \emptyset$ or $P = Q$.

(iv) For every $Q \in \mathcal{K}$, $\operatorname{cl} \overset{\circ}{Q} = Q$.

(v) $Q \in \mathcal{K}^d$ implies that $Q = \bigcup\{\overset{\circ}{P} \mid P \in \mathcal{K}^d$ such that $\overset{\circ}{P} \subset Q\}$.

(vi) If X is a cubical set and $\overset{\circ}{Q} \cap X \neq \emptyset$ for some elementary cube Q, then $Q \subset X$.

A set $Y \subset \mathbb{R}^d$ is called *representable* if it is a finite union of elementary cells. The family of representable sets in $\mathbb{R}^d$ is denoted by $\mathcal{R}^d$.

Proposition 2.3 *Representable sets have the following properties:*

(i) Every elementary cube is representable.

(ii) If $A, B \in \mathcal{R}^d$, then $A \cup B, A \cap B, A \setminus B \in \mathcal{R}^d$.

(iii) A set $X \subset \mathbb{R}^d$ is cubical if and only if it is closed and representable.

(iv) A bounded set $A \subset \mathbb{R}^d$ is representable if and only if for every $Q \in \mathcal{K}^d$, $\overset{\circ}{Q} \cap A \neq \emptyset$ implies $\overset{\circ}{Q} \subset A$.

Let $A \subset \mathbb{R}^d$ be a bounded set. Then the *open hull* of A is

$$\mathrm{oh}\,(A) := \bigcup \{\overset{\circ}{Q} \mid Q \in \mathcal{K}, Q \cap A \neq \emptyset\}, \tag{6}$$

and the *closed hull* of A is

$$\mathrm{ch}\,(A) := \bigcup \{Q \mid Q \in \mathcal{K}, \overset{\circ}{Q} \cap A \neq \emptyset\}. \tag{7}$$

Proposition 2.4 *Assume $A \subset \mathbb{R}^d$. Then*

(i) $\mathrm{oh}\,(A) = \bigcap \{U \in \mathcal{R}^d \mid U$ *is open and* $A \subset U\}$.

(ii) $\mathrm{ch}\,(A) = \bigcap \{B \in \mathcal{R}^d \mid B$ *is closed and* $A \subset B\}$.

3 Cubical Topology

It is obvious that a union of a finite family of cubical sets in $\mathbb{R}^d$ is a cubical set and easy to show that the intersection of any family of cubical sets is a cubical set. Thus the following definition makes sense.

Definition 3.1 The *cubical topology* in $\mathbb{R}^d$ is defined by the family $\mathcal{V}^d$ of *closed sets* given by

$$\mathcal{V}^d := \{X \in \mathbb{R}^d \mid X \text{ is a cubical set}\} \cup \{\emptyset, X\}.$$

More precisely, the family $\mathcal{T}^d$ of *open sets* called the *cubical topology* in $\mathbb{R}^d$ is given by

$$U \in \mathcal{T}^d \text{ if and only if } \mathbb{R}^d \setminus U \in \mathcal{V}^d.$$

Note that open sets, the complements of cubical sets, are unbounded. In particular, representable sets which are open with respect to Euclidean topology are not open in cubical topology. This slight inconvenience may be avoided by restricting the topology to a fixed cubical set $X \subset \mathbb{R}^d$ which is always done in practical applications. Let

$$\mathcal{T}_{|X} := \{U \cap X \mid U \in \mathcal{T}^d\}$$

be the relative cubical topology of X. It is easily verified that

Proposition 3.2 *Let X be a cubical set. A set $U \subset X$ is in $\mathcal{T}_{|X}$ if and only if U is open in the relative Euclidean topology of X and representable.*

It is easy to see that the cubical topology does not satisfy any separation axioms. For example, points in the open interval $(1,2) \subset \mathbb{R}$ cannot be separated in the sense of any axiom. We introduce the following refinement of two axioms of our interest.

Definition 3.3 Let $(X, \mathcal{T})$ be a topological space and $x, y \in X$. We say that

(i) The points x and y are *T_0-separable* if there exists $U \in \mathcal{T}$ which contains exactly one of those two points.

(ii) The points x and y are *T_1-separable* if there exist $U, W \in \mathcal{T}$ such that U contains x and not y and W contains y and not x.

(iii) The points x and y are *T_2-separable* or *Hausdorff-separable* if there exist $U, W \in \mathcal{T}$ such that $U \cap W = \emptyset$, $x \in U$ and $y \in W$.

Proposition 3.4 *Consider the cubical topology $\mathcal{T}^d$ and let $\mathbf{x}, \mathbf{y} \in \mathbb{R}^d$. Then*

(i) The points x and y are T_0-separable if and only if they are in distinct elementary cells $\overset{\circ}{P}$, $\overset{\circ}{Q}$.

(ii) The points x and y are T_1-separable if and only they are in distinct elementary cells $\overset{\circ}{P}$, $\overset{\circ}{Q}$, such that neither $P \subset Q$ nor $Q \subset P$.

(iii) Let X be a cubical set with the restricted cubical topology $\mathcal{T}_{|X}$ and let $x, y \in X$. The points x and y are T_2-separable in X if and only if $\mathrm{oh}\,(x) \cap \mathrm{oh}\,(y) = \emptyset$.

Proof: (i) Suppose that x and y are T_0 separable, and let $U \in \mathcal{T}$ be a set with $x \in U$, $y \notin U$. Then $Y = \mathbb{R}^d \setminus U$ is a cubical set containing y. By Proposition 2.2(i) and Proposition 2.3(iii) both U and Y are unions of elementary cells, hence there exist $P, Q \in \mathcal{K}$ such that $x \in \overset{\circ}{P} \subset U$ and $y \in \overset{\circ}{Q} \subset Y$. Since U and Y are disjoint, so are $\overset{\circ}{P}$ and $\overset{\circ}{Q}$.

Now suppose that there exist distinct cells $\overset{\circ}{P}$ and $\overset{\circ}{Q}$ such that $x \in \overset{\circ}{P}$ and $y \in \overset{\circ}{Q}$. If $x \notin Q$ then we may take $U = \mathbb{R}^d \setminus Q$. Then $x \in U$ and $y \notin U$. If $y \notin P$ then we may take $U = \mathbb{R}^d \setminus P$ and the conclusion follows the same way. If neither of these assumptions hold, then $x \in Q \cap \overset{\circ}{P}$ and $y \in P \cap \overset{\circ}{Q}$. Then Proposition 2.3(iv) implies that $\overset{\circ}{P} \subset Q$ and $\overset{\circ}{Q} \subset P$. By Proposition 2.2(iv), $P = Q$, a contradiction.

(ii) Suppose that x and y are T_1 separable, let $U \in \mathcal{T}$ be a set with $x \in U$, $y \notin U$ and $W \in \mathcal{T}$ be a set with $y \in W$, $x \notin W$. Then $x \in U \setminus W$ and $y \in W \setminus U$. Since U and W are both unions of elementary cells, there are cells $\overset{\circ}{P}$ and $\overset{\circ}{Q}$ such that $x \in \overset{\circ}{P} \subset U \setminus W$ and $y \in \overset{\circ}{Q} \subset W \setminus U$. It remains to show that $P \not\subset Q$ and $Q \not\subset P$. We have $\overset{\circ}{Q} \cap U = \emptyset$. Since U is open in $\mathcal{T}$, it is also open in the Euclidean topology, and since $Q = \operatorname{cl} \overset{\circ}{Q}$, it follows that $Q \cap U = \emptyset$. If $P \subset Q$, we get a contradiction to $\overset{\circ}{P} \subset U$. The argument for $Q \not\subset P$ is analogous.

Now suppose that there exist distinct cells $\overset{\circ}{P}$ and $\overset{\circ}{Q}$ such that $x \in \overset{\circ}{P}$, $y \in \overset{\circ}{Q}$, $P \not\subset Q$, and $Q \not\subset P$. If $x \notin Q$ and $y \notin P$ then we may take $U = \mathbb{R}^d \setminus Q$, $W = \mathbb{R}^d \setminus P$ and the conclusion follows as in the proof of (i). If one of these assumptions fails, for example $x \in Q$, then we show, as in (i), that $\overset{\circ}{P} \subset Q$, so $P = \operatorname{cl} \overset{\circ}{P} \subset Q$, a contradiction.

(iii) By Proposition 2.4(i), $\operatorname{oh}(x)$ and $\operatorname{oh}(y)$ are the smallest open (in the Euclidean topology) representable sets containing respectively x and y. Therefore the conclusion follows from Proposition 3.2. ■

Cubical topology has analogous properties to Zariski topology. This analogy is exhibited in the following definitions and propositions.

Definition 3.5 A topological space $(X, \mathcal{T})$ is called *noetherian* if, given any decreasing family $V_1 \supset V_2 \supset V_3 \supset \cdots$ of closed sets, there exists an integer $n \geq 1$ such that $V_n = V_{n+j}$ for all $j \in \mathbb{N}$.

Proposition 3.6 *The space* $(\mathbb{R}^d, \mathcal{T}^d)$ *is noetherian.*

Proof: Consider a decreasing sequence $V_1 \supset V_2 \supset V_3 \supset \cdots$ of closed sets. If $V_i = \mathbb{R}^d$ for all i or $V_n = \emptyset$ for a sufficiently large n, the conclusion is obviously satisfied, so we may assume that there exists k such that X_i is a cubical set for all $i \geq k$. In in particular, X_k can be written as $X_k = \bigcup_{j=1}^m Q_j$, where $Q_j \in \mathcal{K}^d$. By Proposition 2.1, there exists at most $m3^d$ elementary cubes included in X_k and at most $2^{m3^d} - 2$ proper cubical subsets of X_2. Thus $V_{i+1} = V_i$ for all but finitely many i, and the conclusion follows. ■

Definition 3.7 Let $(X, \mathcal{T})$ be a topological space. A closed set $V \subset X$ is *irreducible* if, given any decomposition $V = V_1 \cup V_2$ with V_1, V_2 closed, we must have $V = V_1$ or $V = V_2$.

Proposition 3.8 *Let $V \in \mathcal{V}^d$. Then V is irreducible if and only if $V = \mathbb{R}^d$ or V is an elementary cube.*

Proof: First, observe that $\mathbb{R}^d$ is irreducible because all other elements of $\mathcal{V}^d$ are cubical sets. Cubical sets are bounded and $\mathbb{R}^d$ is not, so it cannot be a union of two cubical sets. Let $V \subset \mathbb{R}^d$ be an irreducible closed set. If $V \neq \mathbb{R}^d$, then V is a cubical set, so it may be written as a union of n elementary cubes, $V = \bigcup_{i=1}^n Q_i$, $Q_i \in \mathcal{K}^d$. We argue by induction on n that V is an elementary cube. If $n = 1$, $V = Q_1$ is an elementary cube. If $n > 1$, consider the decomposition $V = V_1 \cup V_2$ with $V_1 = Q_1$ and $V_2 = \bigcup_{i=2}^n Q_i$. Since V is irreducible, either $V = V_1$ or $V = V_2$ and the induction hypothesis applies to both cases.

Suppose that $V = Q$ is an elementary cube and consider its decomposition $Q = V_1 \cup V_2$ to two closed, hence cubical, subsets. Then the cell $\overset{\circ}{Q}$ intersects either V_1 or V_2 and the conclusion follows from Proposition2.2(iv). ■

Proposition 3.9 *For any $V \in \mathcal{V}^d$ there exists a unique family of irreducible sets $\{V_k\}_{k=1,2,\ldots n}$ such that $V_j \not\subset V_k$ for $j \neq k$ and $V = \bigcup_{k=1}^n V_k$.*

Proof: The set $V = \mathbb{R}^d$ is irreducible, so we may assume that V is a cubical set, hence, it can be written as a finite union of elements of $\mathcal{K}^d$. By the definition of a maximal face, it can be written as

$$V = \bigcup \{Q \in \mathcal{K}^d \mid Q \in \mathcal{K}_{\max}(X)\}.$$

This union extends over a finite set and it remains to show that it is unique. Suppose that $V = \bigcup_{k=1}^n V_k$ where V_k are irreducible and $V_j \not\subset V_k$. By Proposition 3.8, V_k is an elementary cube for each k. We need to show that

$$\{V_k \mid k = 1, \ldots n\} = \mathcal{K}_{\max}(V).$$

Suppose that $Q \in \mathcal{K}_{\max}(V)$. Since $\bigcup_{k=1}^n V_k = V$, there exists k such that $\mathcal{Q} \cap V_k \neq \emptyset$. By Proposition 2.2(vi), $Q \subset V_k$. Since Q is maximal, $Q = V_k$. Thus

$$\mathcal{K}_{\max}(V) \subset \{V_k \mid k = 1, \ldots n\}. \tag{8}$$

The reverse inclusion is shown by contradiction. Suppose that $V_j \notin \mathcal{K}_{\max}(V)$ for some j. Then there exists $Q \in \mathcal{K}_{\max}(V)$ such that V_j is a proper face of Q. By (8), $Q = V_k$ for some k. But $V_j \not\subset V_k$, a contradiction. ■

We end this section with a remark that the statements of all propositions in this section hold true for relative cubical topology in a given cubical set.

4 Cubical Maps and Their Homology

4.1 Cubical Maps

In Section 2 the definition of homology of a cubical set is recalled. We want now to extend this definition to maps $f : X \to Y$ where $X, Y \subset \mathbb{R}^d$ are cubical sets. Following [5], we would like to define the homomorphism $H_*(f)$ induced in homology for a class maps satisfying the following two conditions:

1. $f(Q) \in \mathcal{K}(Y)$ for every $Q \in \mathcal{K}(X)$,
2. The restriction $f_{|Q}$ to every $Q \in \mathcal{K}(X)$ is affine linear.

These conditions somewhat mimic the definition of simplicial maps in the simplicial homology theory. The difference between these two classes of maps is that, vertices of a simplex are affine independent whereas vertices of an elementary cubes are not. Thus, any simplicial vertex map admits a unique linear extension to each simplex and the passage from a combinatorial concept of a simplicial vertex map to a topological concept of a piecewise continuous map is very natural. This is not true for maps defined on vertices of elementary cubes which causes that the condition (2) is restrictive and not natural. However, the only purpose of this condition is to obtain a continuous map. When the cubical topology introduced in Section 3 is considered, the condition (2) is not necessary and the definition of a cubical map can be stated as follows.

Definition 4.1 Let X, Y be cubical sets. A map $f : X \to Y$ is called a *cubical map* if it is a continuous and closed map with respect to the relative cubical topology in X and Y.

Here is a more explicit equivalent formulation:

Proposition 4.2 *Let X, Y be cubical sets. A map $f : X \to Y$ is a cubical map if and only if it*

(a) $f^{-1}(Q)$ is a cubical set for every $Q \in \mathcal{K}(Y)$,

(b) $f(Q) \in \mathcal{K}(Y)$ for every $Q \in \mathcal{K}(X)$.

Proof: By definition of the relative cubical topology, f is continuous if and only if $f^{-1}(A)$ is a cubical set in X for every cubical set A in Y. Since every

cubical set is a finite union of elementary cubes and a finite union of cubical sets is a cubical set, this is equivalent to (a).

Again by definition, f is a closed map if and only if $f(A)$ is a cubical set in Y for every cubical set A in X. By the previous arguments, this is equivalent to the condition that $f(Q)$ is a cubical set for every $Q \in \mathcal{K}(X)$. We show, by contradiction, that $f(Q)$ must be an elementary cube. Suppose that $f(Q)$ is a cubical set which is not an elementary cube. By Proposition 3.8, there are two cubical sets R and S, neither equal to $f(Q)$, such that $f(Q) = R \cup S$. Then $Q = f^{-1}(R) \cup f^{-1}(S)$. Since Q is irreducible and $f^{-1}(R)$ and $f^{-1}(S)$ are cubical, we must have $Q = f^{-1}(R)$ or $Q = f^{-1}(S)$, so $f(Q) = R$ or $f(Q) = S$, a contradiction. ■

The following property of cubical maps will be used later:

Proposition 4.3 *Let X, Y be cubical sets and $f : X \to Y$ a cubical map. For any $Q \in \mathcal{K}(X)$*

$$\dim f(Q) \leq \dim Q.$$

Proof: We argue by induction on the dimension $k = \dim Q$. If $k = 0$, Q is a singleton and so is $f(Q)$, hence $\dim f(Q) = \dim Q = 0$. Suppose that the conclusion holds for a given $k \geq 0$. Let $Q \in \mathcal{K}_{k+1}(X)$ and $m = \dim f(Q)$. If $m = 0$, we are done. If $m > 0$, there are two opposite faces P_+ and P_- of $f(Q)$ of dimension $m - 1$. Since P_+ and P_- are disjoint elementary cubes, $f^{-1}(P_+)$ and $f^{-1}(P_-)$ are two disjoint proper cubical subsets of Q. Therefore, $\dim f^{-1}(P_+) \leq k$ and $\dim f^{-1}(P_-) \leq k$. By induction hypothesis, $k \leq m - 1$, so $\dim Q = k + 1 \leq m = \dim f(Q)$. ■

The identity map id_X obviously is a cubical map and it is easy to check that the composition $g \circ f$ of two cubical maps is a cubical map. Thus we may form a category Cub whose objects are cubical sets and morphisms are cubical maps.

Note that cubical maps are not necessarily continuous with respect to the Euclidean topology. For example, any surjective function $f : [0, 1] \to [0, 1]$ such that $f^{-1}(\{0, 1\}) = \{0, 1\}$ is a cubical map. We can modify values of a cubical function inside elementary cells freely as long as images of elementary cubes remain the same. Therefore it makes sense to define an equivalence relation for cubical maps $f, g : X \to Y$ by setting $f \sim g$ if and only $f(Q) = g(Q)$ for all $Q \in \mathcal{K}(X)$. The equivalence class of f is called the *cubical class* of f. We will soon see that any cubical map contains, in its cubical class, a representative which is continuous and whose restriction to any elementary cube is affine linear, that is, a linear map possibly composed

with a translation. Before proceeding further, it is helpful to have some examples of cubical maps.

Example 4.4 An inclusion of cubical sets $i : A \hookrightarrow X$ is a cubical map. The following maps of the Euclidean space, when restriced to a cubical set and its image, become cubical maps:

1. Projection $p : \mathbb{R}^d \to R^{d-1}$, $p(\mathbf{x}) = (x_2, x_3, \ldots x_d)$;
2. Coordinate immersion, $j : \mathbb{R}^d \to \mathbb{R}^{d+1}$; $j(\mathbf{x}) = (m, x_1, x_2, \ldots, x_d)$, $m \in \mathbb{Z}$;
3. Translation $\mathbf{x} \mapsto \mathbf{m} + \mathbf{x}$, where $\mathbf{m} \in \mathbb{Z}^d$;
4. Transpose $(x_i, x_{i+1}) \mapsto (x_{i+1}, x_i)$;
5. Inversion $x_i \mapsto -x_i$.

A composition of cubical maps is a cubical map hence more maps can be generated from the above examples. We proceed towards an explicit formula which implies, in particular, that any cubical map can be obtained by composing the maps listed in Example 4.4, up to the cubical equivalence class.

In the sequel, the following notation is be helpful. We first put

$$\mathbb{N}_d = \{1, 2, 3, \ldots, d\}.$$

Next, given an elementary cube $Q = I_1 \times I_2 \times \ldots \times I_d \in \mathcal{K}^d$, we put

$$\mathrm{ess(Q)} := \{\mathrm{i} \in \mathbb{N}_\mathrm{d} \mid \mathrm{I_i} \text{ is non-degenerate}\}.$$

Theorem 4.5 *Let $X \subset \mathbb{R}^d$ and $Y \subset \mathbb{R}^{d'}$ be cubical sets. The cubical class of any cubical map $g : X \to Y$ contains a map f with the following property: For all $Q \in \mathcal{K}(X)$, the restriction of $f = (f_1, f_2, \ldots, f_{d'})$ to Q can be expressed coordinate-wise by the formula*

$$f_i(\mathbf{x}) = m_i + \epsilon_i x_{\mu(i)}, \tag{9}$$

where $i \in \mathbb{N}_{d'}$, $m_i \in \mathbb{Z}$, $\epsilon_i \in \{-1, 0, 1\}$ and μ is a function from $\mathbb{N}_{d'}$ to $\mathbb{N}_d$. Moreover, ϵ_i and m_i are uniquely determined by i, $\mu(i)$ is uniquely determined by i unless $\epsilon_i = 0$, and the function $\nu_{f,Q} : \mathrm{ess(f(Q))} \to \mathrm{ess(Q)}$ such that $\nu_{f,Q}(k) = \mu(k)$ is injective and uniquely determined by f and Q. Conversely, any map defined on elementary cubes in X by (9) is a cubical map.

Proof: The construction of f on each elementary cube Q goes by induction on $k = \dim Q$.

Let $k = 0$. Then $g(Q) \in \mathcal{K}_0^{d'}(Y)$ by Proposition 4.3, so we may write

$$g(Q) = \prod_{i=1}^{d'} [l_i],\ l_i \in \mathbb{Z}.$$

Hence $f_i(Q) = l_i + 0$ is a unique function of the form (9) except that μ arbitrary because $\epsilon_i = 0$. The function $\nu_{g,Q}$ is not defined in this case because ess(g(Q)) $= \emptyset =$ ess(Q). Thus we may put $f_{|Q} := g_{|Q}$.

Suppose that the construction is done for all elementary cubes of dimension $k \geq 0$ so that the restriction of g and f to the k'th skeleton of X,

$$X^{(k)} = \bigcup \{Q \in \mathcal{K}_i(X) \mid i \leq k\}$$

satisfies the conclusion of the theorem. Consider $Q \in \mathcal{K}_{k+1}(X)$.

If ess(g(Q)) $= \emptyset$, we get as previously, $g_i(Q) = l_i + 0$ and $f_{|Q} := g_{|Q}$. If ess(g(Q)) $\neq \emptyset$, choose $n \in$ ess(g(Q)) and let

$$g_n(Q) = [r_n, r_n + 1].$$

Put

$$P = g(Q),$$

$$P_0 = g_1(Q) \times g_2(Q) \times \cdots \times g_{n-1}(Q) \times [r_n] \times g_{n+1}(Q) \times \cdots \times g_{d'}(Q),$$

and

$$Q_0 = Q \cap g^{-1}(P_0).$$

Since P_0 is a proper face of P, $Q_0 \subsetneq Q$. It follows from Proposition 3.8 that Q_0 is an elementary cube. Indeed, suppose that R_1, R_2 are cubical sets such that $Q_0 = R_1 \cup R_2$. Then $g(R_1) \cup g(R_2) = P_0$ but g is a cubical map and P_0 is an elementary cube hence $g(R_1) = P_0$ or $g(R_2) = P_0$. Consequently, $R_1 = Q_0$ or $R_2 = Q_0$. Hence Q_0 is an elementary cube and a proper face of Q. We show that $\dim Q_0 = k$. Indeed, if $\dim Q_0 < k$, there exists $R_0 \mathcal{K}(X)$ such that $Q_0 \subsetneq R_0 \subsetneq Q$ and then $g(Q_0) = P_0 \subsetneq g(R_0) \subsetneq g(Q) = P$. This is impossible because the three sets are elementary cubes and $\dim g(Q) = dim P_0 + 1$. Thus $\dim Q_0 = \dim P_0 = k$.

By the induction hypothesis, f_{Q_0} is defined coordinate-wise by formulas $f_{0i}(\mathbf{x}) = m_{0i} + \epsilon_{0i} x_{\mu_0(i)}$, $i \in \mathbb{N}_{d'}$, ϵ_{0i}, m_{0i} and $\mu_0(i)$ are uniquely determined by i. Since $\dim_{Q_0} = k$, there is a unique $j \in$ ess(Q) such that $j \notin ess(Q_0)$. The j'th component I_j of Q can be written as $I_j = [l_j, l_j + 1]$ and the j'th component I_{0j} of Q_0 is either $[l_j]$ or $[l_j + 1]$.

In the case $I_{0j} = [l_j]$, we put $f_i(\mathbf{x}) = f_{0i}(\mathbf{x})$ for all $i \neq n$ and $f_n(\mathbf{x}) = r_n - l_j + x_j$. This uniquely determines $m_n = r_n - l_j$, $\epsilon_n = 1$ and $\mu(n) = j$.

In the case $I_{0j} = [l_j + 1]$, we put $f_i = f_{0i}$ for all $i \neq n$ and $f_n = r_n + 1 + l_j - x_j$. This uniquely determines $m_n = r_n + 1 + l_j$, $\epsilon_n = -1$ and $\mu(n) = j$.

We show that $\nu_{f,Q} : \mathrm{ess(f(Q))} \to \mathrm{ess(Q)}$ such that $\nu_{f,Q}(k) = \mu(k)$ an injective function. Consider $a, b \in \mathrm{ess(f(Q))}$, $a \neq b$. If $a \neq n$ and $b \neq n$, then $a, b \in \mathrm{ess(f(Q_0))}$ and, by induction hypothesis, $a \neq b$ implies $\nu(a) \neq \nu(b)$. If $a = n \neq b$, then $\nu(a) = \nu(n) = j$ and $b \in \mathrm{ess(f(Q_0))}$. However, j is not in the image of ν_{f,Q_0}, hence $\nu(a) \neq \nu(b)$.

The converse statement is obvious. ■

Note that the coordinate function f_i in the formula (9) for a given elementary cube Q depends only on one coordinate of $\mathbf{x}$, namely $x_{\mu(i)}$. Thus, we may introduce cubical functions $f^i : I_{\mu(i)} \to J_i$ defined on elementary intervals appearing in $Q = \prod_{j=1}^{d} I_j$, $f(Q) = \prod_{i=1}^{d'} J_i$, given by

$$f^i(t) = m_i + \epsilon_i t. \tag{10}$$

With the help of these one-dimensional functions, the formulas (9) for $i \in N_{d'}$ can be replaced by the formula

$$f(\mathbf{x}) = \left(f^1(x_{\mu(1)}), f^2(x_{\mu(2)}), \ldots, f^{d'}(x_{\mu(d')})\right). \tag{11}$$

It is clear that the maps defined by (9) and (11) are affine linear on each elementary cube and since the formulas coincide on common faces of elementary cubes, they extend to a map $f : X \to Y$ which is continuous in Euclidean topology. Thus every cubical class contains a representative which is continuous in the traditional sense.

4.2 Induced Chain Maps

We shall now proceed towards the definition of $H_*(f)$, the homomorphism induced by a cubical map f.

First, let us introduced the following notation. Given $A, B \subset \mathbb{N}$ and a function $\alpha : A \to B$, we define its sign by

$$\operatorname{sgn} \alpha := \begin{cases} (-1)^{\operatorname{card}\{(i,j) \in A^2 | \alpha_j < \alpha_i\}} & \text{if } \alpha \text{ is bijective,} \\ 0 & \text{otherwise.} \end{cases}$$

where card stands for the number of elements of a set.

Definition 4.6 Let $f : X \to Y$ be a cubical map, $X \subset \mathbb{R}^d$ and $Y \subset \mathbb{R}^{d'}$ cubical sets. The *homomorphism induced by f on k-chains* $f_{\#k} : C_k(X) \to C_k(Y)$ is defined on the generators $\widehat{Q} \in \mathcal{K}_k^d(X)$ by induction on d as follows.

(a) Let $k = 0$ and $d = 1$. Then $Q = [l]$ for some $l \in \mathbb{Z}$ and we put

$$f_{\#0}(\widehat{[l]}) = \widehat{[f(l)]}$$

(b) Let $k = 1$ and $d = 1$. Then $Q = [l, l+1]$ for some $l \in \mathbb{Z}$ and we put

$$f_{\#1}(\widehat{[l, l+1]}) = \begin{cases} \widehat{[f(l), f(l+1)]} & \text{if } f(l) < f(l+1) \\ -\widehat{[f(l+1), f(l)]} & \text{if } f(l) > f(l+1) \\ 0 & \text{if } f(l) = f(l+1) \end{cases}$$

(c) Let $d > 1$, $Q = \prod_{i=1}^d I_i$, $\dim f(Q) = n$, and let $l_1 < l_2 < \cdots l_n$ be the indices in ess(f(Q)). We define

$$f_{\#k}(\widehat{Q}) = \operatorname{sgn}(f, Q) \mathop{\Diamond}_{i=1}^{n} f^i_{\#1}(\widehat{I}_{\nu_{f,Q}(l_i)}) \tag{12}$$

where $\operatorname{sgn}(f, Q) := \operatorname{sgn}(\nu_{f,Q})$ is defined in Theorem 4.5, and f^i is defined in (10).

Note that the image of a k-chain is always a k-chain because if $\dim Q \neq \dim f(Q)$ then $\operatorname{sgn}(f, Q) = 0$.

Theorem 4.7 *The family of homomorphisms $f_\# := \{f_{\#k}\} : \mathcal{C}(X) \to \mathcal{C}(Y)$ is a* chain map*, that is, it commutes with the boundary operator. More explicitly, for any $k \in \mathbb{N}, k \neq 0$ we have*

$$\partial_k \circ f_{\#k} = f_{\#k-1} \circ \partial_k. \tag{13}$$

Proof: Obviously it is enough to verify (13) on elements of the canonical basis $\widehat{Q} \in \mathcal{C}(X)$. If $\operatorname{emb} Q = 1$, the verification is straightforward. Thus assume $Q = \prod_{i=1}^d I_i$ with $d > 1$. Let $I_i = [a_i, b_i]$ for some $a_i \in \mathbb{Z}$ and $b_i \in \{a_i, a_i + 1\}$. Let $\mu : \mathbb{N}_{d'} \to \mathbb{N}_d$ be as in Theorem 4.5. Let $A :=$ ess(Q), $B :=$ ess(f(Q)) and $\nu := \nu(f, Q) = \mu_{|B} : B \to A$. If ν is not a bijection then one easily verifies that both sides of (13) are zero. Thus assume that ν is a

bijection. For $i \in B$ put

$$\begin{aligned}
s_i &:= \operatorname{card}\{\nu(j) \in A \mid j < i\} = \operatorname{card}\{j \in B \mid j < i\}, \\
p_i &:= \operatorname{card}\{j \in B \mid j < i \text{ and } \nu(j) > \nu(i)\}, \\
n_i &:= \operatorname{card}\{j \in B \mid j > i \text{ and } \nu(j) < \nu(i)\}, \\
t_i &:= \operatorname{card}\{j \in B \mid \nu(j) < \nu(i)\} = \operatorname{card}\{\nu(j) \in A \mid \nu(j) < \nu(i)\}, \\
B_i &:= B \setminus \{i\}, \\
r_i &:= \operatorname{card}\left\{(l,m) \in B_i^2 \mid l < m \text{ and } \nu(l) > \nu(m)\right\}, \\
\gamma_i &:= (-1)^{\sum_{j=1}^{i-1} \dim f_{\#}^{j}(\widehat{I}_{\nu(j)})}, \\
\epsilon_i &:= \operatorname{sgn}(f,Q)\gamma_i.
\end{aligned}$$

Since ν is bijective, $\dim f_{\#}^{i}(\widehat{I}_{\nu(i)}) = \dim \widehat{I}_{\nu(i)}$, therefore

$$\gamma_i = (-1)^{\sum_{j=1}^{i-1} \dim \widehat{I}_{\nu(j)}} = (-1)^{s_i}.$$

Let

$$\begin{aligned}
Q_a^i &:= \prod_{j=1}^{i-1} I_j \times [a_i] \times \prod_{k=i+1}^{d} I_k, \\
Q_b^i &:= \prod_{j=1}^{i-1} I_j \times [b_i] \times \prod_{k=i+1}^{d} I_k.
\end{aligned}$$

Note that $\operatorname{ess}(Q_a^i) = B_i = \operatorname{ess}(Q_b^i)$, therefore $\operatorname{sgn}(f, Q_a^i) = (-1)^{r_i} = \operatorname{sgn}(f, Q_b^i)$. Denote this common value by δ_i. We have

$$\operatorname{sgn}(f,Q) = (-1)^{\operatorname{card}\left\{(l,m) \in B^2 \mid l < m \text{ and } \nu(l) > \nu(m)\right\}} = (-1)^{r_i + p_i + n_i}.$$

Therefore

$$\delta_i = (-1)^{r_i} = \operatorname{sgn}(f,Q)(-1)^{p_i + n_i}.$$

Consequently

$$\epsilon_i \delta_i = \operatorname{sgn}(f,Q)^2 (-1)^{s_i + p_i + n_i} = (-1)^{t_i}.$$

From equation (3) and definition 4.6 we get

$$
\begin{aligned}
(\partial \circ f)_{\#}(\widehat{Q}) &= \sum_{i=1}^{d} \epsilon_i \big(\mathop{\Diamond}_{h=1}^{i-1} f_{\#}^{h}(\widehat{I}_{\mu(h)}) \big) \diamond \partial f_{\#}^{i}(\widehat{I}_{\mu(i)}) \diamond \big(\mathop{\Diamond}_{h=i+1}^{d} f_{\#}^{h}(\widehat{I}_{\mu(h)}) \big) \\
&= \sum_{i \in B} \epsilon_i \big(\mathop{\Diamond}_{h=1}^{i-1} f_{\#}^{h}(\widehat{I}_{\nu(h)}) \big) \diamond f_{\#}^{i}(\widehat{[b_{\nu(i)}]}) \diamond \big(\mathop{\Diamond}_{h=i+1}^{d} f_{\#}^{h}(\widehat{I}_{\nu(h)}) \big) \\
&\quad - \sum_{i \in B} \epsilon_i \big(\mathop{\Diamond}_{h=1}^{i-1} f_{\#}^{h}(\widehat{I}_{\nu(h)}) \big) \diamond f_{\#}^{i}(\widehat{[a_{\nu(i)}]}) \diamond \big(\mathop{\Diamond}_{h=i+1}^{d} f_{\#}^{h}(\widehat{I}_{\nu(h)}) \big) \\
&= \sum_{i \in B} \epsilon_i \delta_i f_{\#} \Big(\big(\mathop{\Diamond}_{h=1}^{i-1} \widehat{I}_{\nu(h)} \big) \diamond \widehat{[b_{\nu(i)}]} \diamond \big(\mathop{\Diamond}_{h=i+1}^{d} \widehat{I}_{\nu(h)} \big) \Big) \\
&\quad - \sum_{i \in B} \epsilon_i \delta_i f_{\#} \Big(\big(\mathop{\Diamond}_{h=1}^{i-1} \widehat{I}_{\nu(h)} \big) \diamond \widehat{[a_{\nu(i)}]} \diamond \big(\mathop{\Diamond}_{h=i+1}^{d} \widehat{I}_{\nu(h)} \big) \Big) \\
&= f_{\#} \Big(\sum_{i \in B} (-1)^{t_i} \big(\mathop{\Diamond}_{h=1}^{i-1} \widehat{I}_{\nu(h)} \big) \diamond \partial \widehat{I}_{\nu(i)} \diamond \big(\mathop{\Diamond}_{h=i+1}^{d} \widehat{I}_{\nu(h)} \big) \Big) \\
&= f_{\#} \Big(\sum_{l \in A} (-1)^{\mathrm{card}\,\{m \in A | m < l\}} \big(\mathop{\Diamond}_{h=1}^{l-1} \widehat{I}_h \big) \diamond \partial \widehat{I}_l \diamond \big(\mathop{\Diamond}_{h=l+1}^{d} \widehat{I}_h \big) \Big) \\
&= f_{\#} \Big(\sum_{l=1}^{d} (-1)^{\sum_{j=1}^{l-1} \dim \widehat{I}_j} \big(\mathop{\Diamond}_{h=1}^{l-1} \widehat{I}_h \big) \diamond \partial \widehat{I}_l \diamond \big(\mathop{\Diamond}_{h=l+1}^{i-1} \widehat{I}_h \big) \Big) \\
&= f_{\#} \circ \partial(\widehat{Q}).
\end{aligned}
$$

■

The correctness of the following definition is a standard consequence of the property (13) of any chain map on chain complexes.

Definition 4.8 Let $f : X \to Y$ be a cubical map and $f_{\#} : \mathcal{C}(X) \to \mathcal{C}(Y)$ the induced chain map. The homomorphism $H_k(f) : H_k(X) \to H_k(Y)$ induced by $f_{\#}$ on quotient groups is called the *the kth homology of f*. The family of maps $H_*(f) = \{H_k(f)\} : H_*(X) \to H_*(Y)$ is called the *homology map* of f.

Lemma 4.9 *The definition of a chain map induced by a cubical map is functorial in the following sense.*

(a) Given a cubical set X, $(\mathrm{id}_X)_{\#k} = \mathrm{id}_{C_k(X)}$ for all k,

(b) Given two cubical maps $f : X \to Y$ and $g : Y \to Z$ on cubical sets, $g_{\#k} \circ f_{\#k} = (g \circ f)_{\#k}$ for all k.

Proof: Let $X \subset \mathbb{R}^d, Y \subset \mathbb{R}^{d'}$ and $Z \subset \mathbb{R}^{d''}$. It is enough to verify (a) and (b) on elements of the canonical basis $\widehat{Q} \in \mathcal{K}_k^d(X)$. Put $Q = \prod_{i=1}^d I_i$.

(a) Since $\nu_{\mathrm{id}\,_{X,Q}} : \mathbb{N}_d \to \mathbb{N}_d$ is the identity, we have

$$(id_X)_{\#k}(\widehat{Q}) = \mathrm{sgn}(id_X, Q) \overset{d}{\underset{i=1}{\diamondsuit}} (id_X)_{\#1}\widehat{I}_{\nu(i)} = \overset{d}{\underset{i=1}{\diamondsuit}} \widehat{I}_i = \widehat{Q}.$$

(b) Let first $d = d' = d'' = 1$. If $\dim Q = 0$ then $Q = [l]$ for some $l \in \mathbb{Z}$ and

$$(g_{\#0} \circ f_{\#0})\,[l] = g_{\#0}\widehat{[f(l)]} = [\widehat{(g \circ f)(l)}] = (g \circ f)_{\#0}\widehat{[l]}.$$

If $\dim Q = 1$, then $Q = [l, l+1]$ for some $l \in \mathbb{Z}$. Put $a = f(l)$, $b = f(l+1)$, $c = g(a)$, and $d = g(b)$. We have

$$\begin{aligned}
(g_{\#1} \circ f_{\#1})(\widehat{[l, l+1]}) &= \begin{cases} g_{\#1}\widehat{[a,b]} & \text{if } a < b \\ -g_{\#1}\widehat{[b,a]} & \text{if } b < a \\ g_{\#1}0 & \text{if } a = b \end{cases} \\
&= \begin{cases} \widehat{[c,d]} & \text{if } a < b \text{ and } c < d \\ -\widehat{[d,c]} & \text{if } a < b \text{ and } d < c \\ -\widehat{[d,c]} & \text{if } b < a \text{ and } d < c \\ \widehat{[c,d]} & \text{if } b < a \text{ and } c < d \\ 0 & \text{otherwise} \end{cases} \\
&= \begin{cases} \widehat{[c,d]} & \text{if } c < d \\ -\widehat{[d,c]} & \text{if } d < c \\ 0 & \text{otherwise} \end{cases} \\
&= (g \circ f)_{\#1}(\widehat{[l, l+1]}).
\end{aligned}$$

Let now $d, d', d'' \geq 1$ not all equal to 1. We use abbreviations $\nu_f = \nu_{f,Q}$ and $\nu_g = \nu_{f(Q)}g$. We let $k_1 < k_2 < \cdots k_m$ be the essential indices of $f(Q)$ and $l_1 < l_2 < \cdots l_n$ the essential indices of $g(f(Q))$.

By the linearity of $g_\#$ and by (12),

$$\begin{aligned}
(g_{\#k} \circ f_{\#k})(\widehat{Q}) &= g_{\#k}\left(\mathrm{sgn}(f, Q) \overset{m}{\underset{i=1}{\diamondsuit}} f_{\#k}^{k_i}\widehat{I}_{\nu_f(k_i)}\right) \\
&= \mathrm{sgn}(\nu_f)\; g_{\#k}\left(\overset{m}{\underset{i=1}{\diamondsuit}} f_{\#k}^{k_i}\widehat{I}_{\nu_f(k_i)}\right) \\
&= \mathrm{sgn}(\nu_f)\; \mathrm{sgn}(\nu_g) \overset{n}{\underset{j=1}{\diamondsuit}} g_{\#k}^{l_j}\left(f_{\#k}^{\nu_f(l_j)}(\widehat{I}_{\nu_f(\nu_g(l_j))})\right).
\end{aligned}$$

Since $\operatorname{sgn}(\sigma \circ \tau) = \operatorname{sgn}(\sigma)\operatorname{sgn}(\tau)$ for any permutations σ, τ, using the result proved in the case $d = d' = d'' = 1$, we get

$$\begin{aligned}
(g_{\#k} \circ f_{\#k})(\widehat{Q}) &= \operatorname{sgn}(\nu_f \circ \nu_g) \left(\mathop{\Diamond}_{j=1}^{n} (g^{l_j} \circ f^{\nu(l_j)})_{\#k} \widehat{I}_{\nu_f \circ \nu_g(l_j)} \right) \\
&= \operatorname{sgn}(\nu_f \circ \nu_g) \left(\mathop{\Diamond}_{j=1}^{n} (g \circ f)^{l_j}_{\#k} \widehat{I}_{\nu_f \circ \nu_g(l_j)} \right) \\
&= \operatorname{sgn}(\nu_{g \circ f}) \left(\mathop{\Diamond}_{j=1}^{n} (g \circ f)^{l_j}_{\#k} \widehat{I}_{\nu_{f \circ g}(l_j)} \right) = (g \circ f)_{\#k}
\end{aligned}$$

■

By standard homological algebra arguments, Lemma 4.9 implies the following.

Theorem 4.10 *H_* is a functor from* Cub *to the category of graded groups. More explicitly,*

(a) Given a cubical set X, $H_*(\mathrm{id}_X) = \mathrm{id}_{H_*(X)}$,

(b) Given two cubical maps $f : X \to Y$ and $g : Y \to Z$ on cubical sets, $H_*(g) \circ H_*(f) = H_*(g \circ f)$.

The following examples are related to first three maps in Example 4.4.

Example 4.11 Assume $A \subset X$ are cubical sets. If $i : A \to X$ is the inclusion map then $i_\# : \mathcal{C}(A) \to \mathcal{C}(X)$ is also an inclusion map.

Example 4.12 Consider the elementary cubes $Q = [0,1]^d$, $Q' = [0,1]^{d-1}$ and the projection map $p : Q \to Q'$ given by

$$p(x_1, x_2, x_3, \ldots, x_d) := (x_2, x_3, \ldots, x_d).$$

Any face P of Q can be written as $P = I_1 \times P'$, where I_1 can be $[0,1]$, $[0]$, or $[1]$, and $P' = p(P)$ is a complementary face of P. The induced chain map $p_\# : \mathcal{C}(Q) \to \mathcal{C}(Q')$ is given by

$$\pi_{\#k}(\widehat{P}) := \begin{cases} \widehat{P'} & \text{if } I_1 = [0] \text{ or } I_1 = [1], \\ 0 & \text{otherwise.} \end{cases} \tag{14}$$

Example 4.13 Let Q and Q' be as in Example 4.12. The map $j : Q' \to Q$ given by

$$j(x_1, x_2, x_3, \ldots, x_{d-1}) := (0, x_1, x_2, \ldots, x_{d-1})$$

is a cubical map, and the induced chain map $p_\# : \mathcal{C}(Q') \to \mathcal{C}(Q)$ is given by

$$j_{\#k}(c) := \widehat{[0]} \diamond c.$$

Note that $pj = \mathrm{id}_{Q'}$, therefore $p_\# j_\# = (pj)_\# = \mathrm{id}_{\mathcal{C}(Q')}$. Next, $j_\# p_\# = (jp)_\#$ is chain homotopic to $\mathrm{id}_{\mathcal{C}(Q)}$, with the chain homotopy $D_k : C_k(Q) \to C_{k+1}(Q)$ given by

$$D_k(\widehat{P}) := \begin{cases} \widehat{[0,1]} \diamond \widehat{P'} & \text{if } I_1 = [1], \\ 0 & \text{if } I_1 = [0], \\ 0 & \text{if } I_1 = [0,1], \end{cases}$$

where $P = I_1 \times P' \in \mathcal{K}(Q)$ is as in Example 4.12. It follows that $H_*(pj) : H_*(Q') \to H_*(Q)$ is the inverse of $H_*(pj) : H_*(Q) \to H_*(Q')$. Consequently, $H_*(Q') \cong H_*(Q)$.

From the result presented in Example 4.13, one can conclude, by induction on d, that $Q = [0,1]^d$ is *acyclic*, that is, its homology is isomorphic to homology of a point:

$$H_k(Q) \cong \begin{cases} \mathbb{Z} & \text{if } k = 0, \\ 0 & \text{otherwise.} \end{cases}$$

That is probably the simplest way of proving it without using the homotopy invariance theorem, whose proof is more involved.

4.3 Combinatorial Vietoris Theorem

Here is a combinatorial version of the Vietoris Theorem [6].

Theorem 4.14 *Let X, Y be cubical sets and $f : X \to Y$ a cubical map. If f is surjective and $f^{-1}(Q)$ is acyclic for each $Q \in \mathcal{K}(Y)$ then $f_* : H_*(X) \to H_*(Y)$ is an isomorphism.*

Proof: We construct by induction a chain map

$$\psi = \{\psi_k : C_k(X) \to C_k(Y)\}$$

and we prove that it is a homological inverse of f_*.

Let $k = 0$. Let $\widehat{Q} \in C_0(X)$ be an elementary 0-chain. Since f is surjective and cubical, there exists a $P \in \mathcal{K}_0(X)$ such that $f(P) = Q$. Then $f_\#(\widehat{P}) = \widehat{Q}$ and we put $\psi_0(\widehat{Q}) := \widehat{P}$.

Suppose now that $k \geq 1$ and $\psi_i : C_i(X) \to C_i(Y)$ is constructed for $i = 1, 2, \ldots k-1$ so that

$$\left|\psi_i(\widehat{Q})\right| \subset f^{-1}(Q) \text{ for all } Q \in \mathcal{K}_i(Y) \tag{15}$$

$$\psi_{i-1}\partial_i = \partial_i\psi_i. \tag{16}$$

Note that then for any $Q \in \mathcal{K}_k(Y)$

$$\left|\psi_{k-1}\left(\partial\widehat{Q}\right)\right| \subset f^{-1}\left(\left|\partial\widehat{Q}\right|\right) \subset f^{-1}\left(\left|\widehat{Q}\right|\right) \subset f^{-1}(Q).$$

By the induction hypothesis, $\psi_{k-1}\partial\widehat{Q} \in \mathbb{Z}_{k-1}(f^{-1}(Q))$. Since $f^{-1}(Q)$ is acyclic, its reduced homology $\tilde{H}_*(f^{-1}(Q))$ is zero. Therefore, there exists a $c \in C_k(f^{-1}(Q))$ such that $\partial c = \psi_{k-1}\partial\widehat{Q}$. In the case $k > 1$ this is straightforward while in the case $k = 1$ it follows from the fact that Q is an interval so, by the definition of Ψ_0, $\psi_0\partial\widehat{Q}$ is a difference of two vertices, thus it is a reduced cycle. We put $\psi_k\widehat{Q} := c$.

Thus the map ψ is constructed. We will show now that

$$f_\# \circ \psi = \mathrm{id}_{C(Y)}. \tag{17}$$

The proof is again by induction. For $k = 0$ the assertion follows immediately from the definition of ψ_0. Suppose that $\psi_{\#i} \circ \psi_i = \mathrm{id}_{C_i(Y)}$ for $0 \leq i \leq k-1$. Given any $Q \in \mathcal{K}_k(Y)$, we have

$$\partial\widehat{Q} = f_{\#k-1} \circ \psi_{k-1}(\partial\widehat{Q}) = \partial_k \circ f_{\#k} \circ \psi_k(\widehat{Q})$$

and, by the definition of ψ,

$$\left|f_{\#k} \circ \psi(\widehat{Q})\right| \subset f(\left|\psi(\widehat{Q})\right|) \subset f(f^{-1}(Q)) \subset Q.$$

Therefore $f_{\#k} \circ \psi_k(\widehat{Q})$ is a k-chain which has the same boundary as $\widehat{Q}$. It follows that $f_{\#k} \circ \psi_k(\widehat{Q}) - \widehat{Q}$ is a cycle in Q. However, $\tilde{H}_*(Q) = 0$, hence, every k-cycle in Q is a boundary. Since $\dim Q = k$, the only $(k+1)$-dimensional boundary in Q is zero. Thus

$$f_{\#k} \circ \psi(\widehat{Q}) = \widehat{Q}.$$

In the last step we will show that $\psi \circ f_\#$ is chain homotopic to $\mathrm{id}_{C(X)}$. To do this we construct by induction a chain homotopy

$$D = \{D_i : C_i(X) \to C_{i+1}(X)\}$$

such that

$$\partial_{i+1} \circ D_i + D_{i-1} \circ \partial_i = \psi_i \circ f_{\#i} - \mathrm{id}_{C_i(X)} \tag{18}$$

$$|D_i(c)| \subset f^{-1}(Q) \text{ for any } c \in C_i(f^{-1}(Q)) \text{ and } Q \in \mathcal{K}_i(Y). \tag{19}$$

Let $k = 0$ and take any $P \in \mathcal{K}_0(X)$. Let $Q := f(P)$ and let $c := \psi_0(\widehat{Q})$. Then $\psi_0 \circ f_{\#}(\widehat{P}) = c$. Since $|c| \cup \left|\widehat{P}\right| \subset f^{-1}(Q)$, we have $\left|c - \widehat{P}\right| \subset f^{-1}(Q)$. Since $\tilde{H}_*(f^{-1}(Q)) = 0$, there exists a $c' \in C_1(f^{-1}(Q))$ such that

$$\partial c' = c - \widehat{P} = \left(\psi_0 \circ f_{\#0} - \mathrm{id}_{C_0(X)}\right)(\widehat{P}).$$

We put $D_0(\widehat{P}) := c'$.

Now suppose that for $i = 0, 1, 2, \ldots k-1$ the maps $D_i : C_i(X) \to C_{i+1}(X)$ are constructed so that properties (18) and (19) are satisfied. Take any $P \in \mathcal{K}_k(X)$. Let $Q := f(P)$ and let $c := \psi_k(\widehat{Q}) = \psi_k(f_{\#}(\widehat{P}))$. Since both $\left|\widehat{P}\right|$ and $|c|$ are in $f^{-1}(Q)$, the induction hypothesis (19) and the subadditivity of support in [8, Chapter 2, Proposition 2.19(iv)] imply that

$$\left|c - \widehat{P} - D_{k-1}\partial_k\widehat{P}\right| \subset |c| \cup \left|\widehat{P}\right| \cup \left|D_{k-1}\partial_k\widehat{P}\right| \subset f^{-1}(Q).$$

Since $\tilde{H}_*(f^{-1}(|Q|)) = 0$, there exists a $c' \in C_{k+1}(f^{-1}(Q))$ such that

$$\partial c' = c - \widehat{P} - D_{k-1}\partial_k\widehat{P} = \left(\psi_k \circ f_{\#k} - \mathrm{id}_{C_k(X)} - D_{k-1}\partial_k\right)(\widehat{P}).$$

It remains to define $D_k(\widehat{P}) := c'$. Then (18) is obviously satisfied and (19) follows when the construction is completed for all cubes P in $f^{-1}(Q)$. ■

5 Homology of continuous maps via cubical maps.

From now on, by a continuous map we mean a map which is continuous with respect to the Euclidean topology. As we pointed out in Section 4.1, the class of cubical maps is small. In particular it is to small to obtain a counterpart of the theorem stating that every continuous map may be approximated by simplicial maps. Since this approximation theorem is crucial in the definition of simplicial homology of continuous maps, one can see that there is no way to carry over the definition of the homology of a continuous map from the simplicial case to the cubical case by means of approximation. One way to overcome this difficulty is by considering cubical multivalued maps and their homology. This approach is presented in [8]. The main difficulty of this approach does not lie in the construction of the multivalued map itself but

in the construction of the so called chain selector of the multivalued map. In particular it requires solving a large linear equation for each elementary cube in the domain of the multivalued map.

However, it turns out that approximation, which is convenient in the case of simplicial homology, may be replaced by Cartesian approach, which is natural for cubical homology. This approach is used in [10] to present a new algorithm for computing homology of continuous maps. Since the presentation there is technical and oriented on efficiency, in this section we will describe the Cartesian approach without all the improvements designed for the efficiency but hiding the main idea.

The construction is based on the definition of the homology of a multivalued map via projections from the graph given in [6] and an idea from [1]. Let X, Y be two cubical sets and let $f : X \to Y$ be continuous in Euclidean topology. Our goal is to define the homology of f in terms of homology of some cubical maps. Recall that the graph of f is the set

$$\mathrm{graph(f)} := \{(\mathrm{x}, \mathrm{y}) \in \mathrm{X} \times \mathrm{Y} \mid \mathrm{y} = \mathrm{f(x)}\}.$$

Obviously, graph(f) is not a cubical set unless f is locally constant. However, we may consider a cubical set $Z \subset X \times Y$ such that graph(f) $\subset$ Z. Let $p_Z : Z \to X$ and $q_Z : Z \to Y$ denote projections respectively to X and Y. Then we have the following commutative diagram of continuous maps.

$$\begin{array}{ccccc} & & Z & & \\ & \swarrow p_Z & & \searrow q_Z & \\ X & & \xrightarrow{f} & & Y \end{array} \tag{20}$$

We know from Example 4.4 that p_Z and q_Z are cubical maps and therefore their homology is well defined. Since homology is functorial, the homology of f must satisfy

$$H_*(f) \circ H_*(p_Z) = H_*(q_Z).$$

This may be solved for $H_*(f)$ if $H_*(p_Z)$ is an isomorphism. Since obviously p_Z is surjective, by Theorem 4.14 $H_*(p_Z)$ is an isomorphism if for every $x \in X$ the set

$$p_Z^{-1}(x) = \{x\} \times Y \ \cap \ Z \tag{21}$$

is acyclic. The simplest candidate for Z is $\mathrm{ch}\,(f)$, the closed hull of f in $X \times Y$. In practice, it often fulfils the acyclicity condition of (21). In the case when the acyclicity condition of (21) fails, one has to go through the process of subdivision or rescaling, similarly as in the multivalued approach presented in [8]. One can prove that with a sufficiently large subdivision

or rescaling the closed hull of the graph satisfies the acyclicity condition of (21).

6 Algorithms

In this section we present the algorithms, which compute the homology of a cubical map and a continuous map. We use the notation and the syntax of algorithms introduced in [8]. In particular let us recall the following notation.

```
typedef endpoint := (left, right);
typedef interval := hash{endpoint} of int ;
typedef cube := array[1 : ] of interval;
typedef chain := hash{cube} of int ;
typedef chainMap = array[0 : ] of hash{cube} of chain;
```

To store a cubical map it is natural to use the following data structure.

```
typedef cubicalMap := hash{ cube} of cube;
```

The algorithm computing the homology of a cubical map is straightforward. It consists of two steps. The first step is based on Definition 4.6 and produces the associated chain map. Then a straightforward to implement algorithm `homologyOfChainMap` is used to get the homology of the chain map. Here is a possible implementation.

Algorithm 6.1 Homology of a cubical map

```
function homologyOfCubicalMap(cubicalMap m)
chainMap phi := ();
for i := 1 to lastIndex(m) do
    for each Q in keys(m[i]) do
        if dim(Q) = dim(m[i]{Q)});
            phi[Q] := sgn(m, Q)m[i]{Q)};
        endif;
    endfor;
endfor;
return homologyOfChainMap(phi);
```

Now we are ready to present the prototype of an algorithm computing homology of a continuous map. Of course the fundamental question is to what class of continuous maps we can apply the algorithm. Obviously it is

not possible to apply it to all continuous map, because there is uncountably many of them. One has to choose a suitable countable subclass. What matters is that for the continuous maps in the class one should be able to construct the closed hull of the graph. This may be done in many ways and we do not want to go into details here. The typical approach is based on interval arithmetic [11]. Some ways to achieve this task for certain classes of continuous functions are discussed in [8], [13] and [14]. For the sake of this paper we simply assume that a suitable class of continuous functions is available, the elements of this class can be stored in the data structure `contMap` and algorithm `closedHullOfGraph` finding the closed hull of the graph of a continuous map is given. We also assume that `projection` is an algorithm which given a set $Z \subset X \times Y$ and X or Y returns the projection of Z on X or respectively Y. The algorithm is straightforward to implement.

Algorithm 6.2 Homology of a continuous map

```
function homologyOfContMap(cubicalSet X, Y, contMap f)
Z := closedHullOfGraph(X, Y, f);
p := projection(Z, X);
q := projection(Z, Y);
p := homologyOfCubicalMap(p);
q := homologyOfCubicalMap(q);
return q ∘ p^{-1};
```

Theorem 6.3 *Assume Algorithm 6.2 is called with* `f` *representing a continuous map* f*. If the cubical set represented by* `Z` *satisfies the acyclicity condition of (21), then the algorithm stops and returns the homology of* f*.*

Proof: The proof of this theorem follows immediately from the discussion in Section 5. ■

The strength of Algorithm 6.2 lies in the fact that one avoids solving a large number of large linear equations what is needed in the algorithm presented in [8]. However, a direct application of Algorithm 6.2 would not be efficient for another reason. The problem is that with introducing the graph one raises the dimension of the problem from the maximum of dimensions of the cubical sets X and Y to the sum of these dimensions. The solution is to perform some preprocessing, which allows one to replace the graph by another set in $X \times Y$ whose dimension is the same as the dimension of X. The preprocessing is quite complicated but leads to an algorithm which has been implemented and performs well in concrete applications. The details are presented in [10].

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