

ANALYSIS SITUS

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SECOND EDITION

x 26142L
Op 41557

NEW YORK
PUBLISHED BY THE
AMERICAN MATHEMATICAL SOCIETY
501 WEST 116TH STREET
1931

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PREFACE TO THE SECOND EDITION

The second edition is essentially a reprint of the first, prepared in response to the demand which has arisen for copies of the book and in the hope that it will be a useful adjunct to the more modern and extensive books on the same subject by my colleagues Lefschetz and Alexander. In correcting such errors as have come to my attention the original text has been changed as little as possible, and the changes have not altered the point of view of the original. The chief changes are in the definition of oriented circuit, which has caused a rearrangement at the beginning of Chapter IV, and in the correction of the proof of the invariance of the coefficients of torsion in Chapter IV together with the corresponding discussion of the invariants of a group in Chapter V.

My thanks are due to several colleagues who have sent in corrections, particularly to Messrs. Alexander Lefschetz, Morse Nielsen and Pfeiffer. I owe most of all to Dr. A. B. Brown who has done most of the work of reconstructing faulty proofs and definitions and incorporating changes in the text in such a way as to preserve a self-consistent whole.

At the suggestion of Professor Lefschetz I am including as appendices at the end of the volume a paper on Intersection Numbers which was written as a part of the original book and the paper by Philip Franklin and myself on Matrices whose Elements are Integers which was added for reference in this book.

AUTHOR'S PREFACE

The Cambridge Colloquium Lectures on Analysis Situs were intended as an introduction to the problem of discovering the n -dimensional manifolds and characterizing them by means of invariants. For the present publication the material of the lectures has been thoroughly revised and is presented in a more formal way. It thus constitutes something like a systematic treatise on the elements of Analysis Situs. The author does not, however, imagine that it is in any sense a definitive treatment. For the subject is still in such a state

that the best welcome which can be offered to any comprehensive treatment is to wish it a speedy obsolescence. The definition of a manifold which has been used is that which proceeds from the consideration of a generalized polyhedron consisting of n -dimensional cells. The relations among cells are described by means of matrices of integers and the properties of the manifolds are obtained by operations with the matrices. The most important of these matrices were introduced by H. Poincaré to whom we owe most of our knowledge of n -dimensional manifolds* for the cases in which $n > 2$. But the author also found convenient to employ certain more elementary matrices of incidence whose elements are reduced modulo 2, from which the Poincaré matrices can be derived.

The operations on the matrices lead to combinatorial results which are independent of the particular way in which a manifold is divided into cells and therefore lead to theorems of

Poincaré's work is contained in the following four memoirs: Analysis Situs, Journal de l'École Polytechnique, 2d Ser., Vol. 1 (1895); Complément à l'Analysis Situs, Rendiconti del Circolo Matematico di Palermo, Vol. 13 (1898); Second Complément, Proceedings of the London Mathematical Society, Vol. 32 (1900); Cinquième Complément, Rendiconti, Vol. 18 (1904). The third and fourth Compléments deal with applications to Algebraic Geometry, into which we do not go.

Analysis Situs. The proof that this is so is based on an article by J. W. Alexander in the Transactions of the American Mathematical Society, Vol. 16 (1915), p. 148. The continuous transformations and the singularities (in the way of overlapping, etc.) which are allowed in this proof are completely general, so that we are able to avoid the difficulties, foreign to Analysis Situs, which beset those treatments of the subject which restrict attention to analytic transformations or singularities.

It will be seen that, aside from this one question which has to be dealt with in order to give significance to the combinatorial treatment, we leave out of consideration all the work that has been done on the point-set problems of Analysis Situs and on its foundation in terms of axioms or definitions other than those actually used in the text. We have also been obliged by lack of space to leave out all reference to the applications. We have not even given a definition of an n -cell by means of a set of equations and inequalities, or the discussion of orientation by means of the signs of determinants. These are to be found in very readable form in Poincaré's first paper, where they are given as the basis of his work. They belong properly, however, to the applications of the subject. For in nearly all cases when Poincaré (or anyone else) has proved a theorem of Analysis Situs, he has been obliged to set up a machinery which is equivalent to a set of matrices.

No attempt has been made to give a complete account of the history and literature of the subject. These are covered for the period up to 1907 by the article on Analysis Situs by Dehn and Heegard in the Encyklopädie (Vol. III₁, p. 153); and the more important works subsequent to that date which bear on our part of the subject are referred to in Chap. V. I take pleasure in acknowledging my indebtedness to Professor J. W. Alexander who has read the manuscript and made many valuable suggestions, and also to Dr. Philip Franklin who has helped with the manuscript, the drawings, and the proof-sheets.

PRINCETON, MAY, 1921.

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CHAPTER I

LINEAR GRAPHS

Fundamental Definitions

1. We shall presuppose a knowledge of some of the elementary properties of the real Euclidean space of n dimensions ($n \leq 3$ for the first two chapters). In such a space, the points collinear with and between two distinct points constitute a *segment* or *one-dimensional simplex* whose *ends* or *vertices* are the given points. The ends are not regarded as points of the segment. For obvious reasons of symmetry, a single point will be referred to as a *0-dimensional simplex*.

2. Consider any set of objects in (1-1) correspondence* with the points of a segment and its two ends. The objects corresponding to the points of the segment constitute a *one-dimensional cell* or *1-cell* and those corresponding to the ends constitute the *ends* or *boundary* of the 1-cell. In like manner a single object may be referred to as a *0-cell*.

In the cases which are usually considered the objects which constitute a cell and its boundary are points of a k -space and the correspondence which defines the cell is continuous. Consequently a 1-cell is an arc of curve joining two distinct points. In the general case, however, it would be meaningless to say that the correspondence was continuous, because continuity implies previously determined order relations, and here the order relations of a cell are determined by means of the defining correspondence.

The objects which constitute a cell and its boundary will always be referred to as "points" in the following pages.

* By (1-1) correspondence we mean a correspondence which is one-to-one reciprocal; i. e., a (1-1) correspondence between two sets $[A]$ and $[B]$ is such that each A corresponds to one and only one B and each B is the correspondent of one and only one A .

The order relations among any set of points on the cell or its boundary are by definition identical with those of the corresponding points of the segment and its boundary. Hence, in particular, a point P is a *limit point* of a set of points $[X]$ of a cell and its boundary if and only if the corresponding point P of the segment is a limit point of the corresponding set of points $[X]$ of the segment and its boundary.

A *continuous transformation* of a cell and its boundary into itself or into another cell and its boundary is now defined

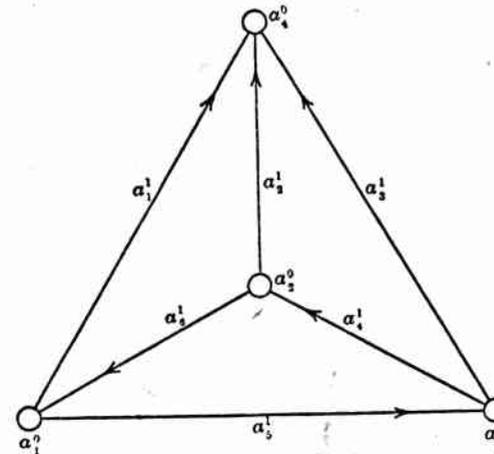


FIG. 1.

as a transformation of the cell and its boundary which if it carries a set $[X]$ to a set $[X']$ carries every limit point of $[X]$ to a limit point of $[X']$.

3. A *zero-dimensional complex* is a set of distinct 0-cells, finite in number. A *one-dimensional complex* or a *linear graph* is a zero-dimensional complex together with a finite number of 1-cells bounded by pairs of its 0-cells, such that no two of the 1-cells have a point in common and each 0-cell is an end of at least one 1-cell. Let us denote the number of 0-cells by α_0 and the number of 1-cells by α_1 . The 0-cells are sometimes called *vertices* and the 1-cells *edges*.

For example, the vertices and edges of a tetrahedron (Fig. 1) constitute a linear graph for which $\alpha_0 = 4$ and $\alpha_1 = 6$. A linear graph is not necessarily assumed to lie in any space, being defined in a purely abstract way. It is obvious, however, that if α_0 points be chosen arbitrarily in a Euclidean three-space they can be joined by pairs in any manner whatever by α_1 non-intersecting simple arcs. Therefore, any linear graph may be thought of as situated in a Euclidean three-space.

For some purposes it is desirable to use the term one-dimensional complex to denote a more general set of 1-cells and 0-cells than that described above. For example, a 1-cell and its two ends form a one-dimensional complex according to the definition above, but a 1-cell by itself or a 1-cell and one of its ends do not. In the following pages we shall occasionally refer to an arbitrary subset of the 1-cells and 0-cells of a linear graph as a *generalized one-dimensional complex*.

4. A transformation F of a set of points $[X]$ of a complex C_1 into a set of points $[X']$ of the same or another complex is said to be *continuous* if and only if it is continuous in the sense of § 2 on each complex composed of a 1-cell of C_1 and its ends (i. e., if the transformation effected by F on those X 's which are on such a 1-cell and its ends is continuous). A (1-1) continuous transformation of a complex into itself or another complex is called, following Poincaré, a *homeomorphism*. The inverse transformation is easily proved to be continuous. Two complexes related by a homeomorphism are said to be *homeomorphic*.

The set of all homeomorphisms by which a linear graph is carried into itself obviously forms a group. Any theorem about a linear graph which states a property which is left invariant by all transformations of this group is a theorem of one-dimensional Analysis Situs. The group of homeomorphisms of a linear graph is its *Analysis Situs group*.

Order Relations on Curves

5. By an *open curve* is meant the set of all points of a complex composed of a 1-cell and its two ends. By

a *closed curve* is meant the set of all points of a complex C_1 consisting of two distinct 0-cells a_1^0, a_2^0 and two 1-cells a_1^1, a_2^1 , each of which has a_1^0 and a_2^0 as ends but which have no common points (Fig. 2). The most elementary theorems about curves are those which codify the order relations. They may be stated (without proof) as follows:

Let us denote a 1-cell and its ends by a^1, a_1^0 and a_2^0 . If a_3^0 is any point of a^1 , there are two 1-cells a_1^1 and a_2^1 such that a_1^1 has a_1^0 and a_3^0 as its ends, a_2^1 has a_3^0 and a_2^0 as its ends, and every point of a^1 is either on a_1^1 or a_2^1 or identical with a_3^0 . The 1-cell a^1 is said to be *separated* into the 1-cells a_1^1 and a_2^1 by the 0-cell a_3^0 .

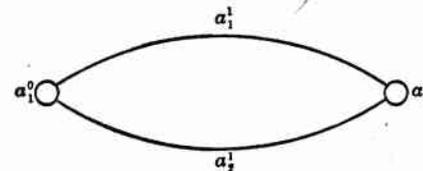


Fig. 2.

A 0-cell is said to be *incident* with a 1-cell if and only if it is an end of the 1-cell; and under the same conditions the 1-cell is said to be incident with the 0-cell. It follows directly from the theorem on separation in the paragraph above that n distinct points of the 1-cell a^1 determine $n+1$ 1-cells such that the n points (or 0-cells) may be denoted by $b_1^0, b_2^0, \dots, b_n^0$ and the $n+1$ 1-cells by $b_1^1, b_2^1, \dots, b_{n+1}^1$ in such a way that each cell is incident with the cell which directly precedes or directly follows it in the sequence $a_1^0, b_1^1, b_1^0, b_2^1, \dots, b_n^0, b_{n+1}^1, a_2^0$.

If $b_1^0, b_2^0, \dots, b_n^0$ are n distinct points of a *closed curve*, the remaining points of the curve constitute n 1-cells b_i^1 ($i = 1, 2, \dots, n$), no two of which have a point in common, such that each b_i^0 is incident with just two of them.

6. A little reflection will convince the reader that many of the theorems about functions of one real variable and

about linear sets of points belong to one-dimensional Analysis Situs. As an example we may cite the theorem that any nowhere dense perfect set of points on a closed curve can be transformed into any other such set by a (1-1) continuous transformation of the curve. The Heine-Borel theorem is another case in point.

(The theorems of Analysis Situs may be divided somewhat roughly into two classes, those dealing essentially with continuity considerations (of which the theorem on perfect sets of points cited above may serve as an illustration), and those having an essentially combinatorial character.) It is the theorems of the latter class which will occupy most of our attention in the following pages, though we shall continually make use of theorems of the former class without proving them.

Singular Complexes

7. Let F be a correspondence between a 0-dimensional complex C_0 and a set of points $[P]$ of any complex C (for the present, C is 0- or 1-dimensional) in which each point of C_0 corresponds to a single P and each P is the correspondent of one or more points of C_0 . The object obtained by associating any point X of C_0 with the point P which is its image under F will be denoted by $F(X)$ and called a point on C ; it is said to *coincide* with P and P to coincide with it. The set of all points $F(X)$ on C is called a 0-dimensional complex on C . If any P is the correspondent of more than one point X of C_0 , P is called a *singular point* and the complex on C is said to be *singular*.

8. Let C_1 be a generalized one-dimensional complex and let F be a continuous correspondence between C_1 and a set of points $[P]$ of a complex C , in which each point of C_1 corresponds to a single P and each P is the correspondent of at least one point of C_1 . The object obtained by associating any point X of C_1 with the point P which is its image under this correspondence will be called a *point on C* and is uniquely denoted by the functional notation $F(X)$; it is said to *coincide* with P and P is said to *coincide* with it. The point $F(X_1)$

is called a *limit point* of the points $F(X)$ if X_1 is a limit point of the points X . The set of all points $F(X)$ on C is in a (1-1) continuous correspondence with the points of C_1 and thus constitutes a one-dimensional complex C'_1 identical in structure with C_1 . The one-dimensional complex C'_1 is said to be *on C* . If any of the points P is the correspondent under F of more than one point of C_1 , C'_1 is called a *singular complex on C* and the point P in question a *singular point*. If the correspondence F is (1-1), C'_1 is said to be *non-singular*.

It is to be emphasized that in the definitions above F is a perfectly general continuous function. Thus, for example, all the points of a 1-cell of C_1 may be imaged on a single point of C . In the rest of this chapter we shall be referring to non-singular complexes more often than to singular ones. We shall therefore understand that a complex is non-singular unless the opposite is stated.

9. Let P be any point of a generalized one-dimensional complex C_1 . If P is a point of a 1-cell of C_1 let Q_1 and Q_2 be two points of this 1-cell such that P is between them. If P is a vertex, let Q_1, Q_2, \dots, Q_j be a set of points, one on each 1-cell of which P is an end. The set of points composed of P and of all points between P and the points Q_1, Q_2, \dots, Q_j is called a *neighborhood* of P .

A generalized one-dimensional complex C'_1 which is on C_1 is said to *cover C_1* in case there is at least one point of C'_1 on each point of C_1 and there exists for every point of C'_1 a neighborhood which is a non-singular complex on C_1 . In case the number of points of C'_1 which coincide with a given point of C_1 is finite and equal to n for every point of C_1 , C'_1 is said to *cover C_1 n times*.

The only connected complex which can cover a 1-cell is a 1-cell, or a subdivision of a 1-cell such as is described in § 5, and it can cover it only once. A *closed curve*, on the other hand, can be covered any number of times by another closed curve.

The truth of the latter statement may be seen very simply as follows. Let C_1 and C'_1 be two circles in a Euclidean plane. Denote any point on C_1 by a coordinate θ ($0 < \theta \leq 2\pi$), and

any point on C'_1 by θ' ($0 < \theta' \leq 2\pi$). Let each point, θ , of C_1 correspond to the n points

$$\theta' = \frac{\theta}{n}, \quad \theta' = \frac{2\theta}{n}, \quad \dots, \quad \theta' = \frac{(n-1)\theta}{n}, \quad \theta' = \theta,$$

of C'_1 . In case $n = 2$, for example, a pair of opposite points of C'_1 corresponds to a single point of C_1 .

The Simplest Invariants

10. One of the first objects of Analysis Situs is to find the numerical invariants of complexes under the group of homeomorphisms. By an invariant under this group we mean a number $I(C)$ determined by a complex C in such a way that if C' be any complex homeomorphic with C , the number $I(C')$ determined in the same way for C' is the same as $I(C)$.

11. Starting with any point O of a complex C_1 consider all points of C_1 which can be joined to this one by open curves, singular or not,* on C_1 . This set of points will contain all points of a certain set of 0-cells and 1-cells of C_1 (a sub-complex of C_1) which we may call C'_1 . Since any two points of C'_1 can be joined to O by open curves, they can be joined to each other by an open curve. Hence the same set of points is determined if any other point of C'_1 replace O in the definition of C'_1 .

Since C_1 is composed of a finite number of 0-cells and 1-cells altogether, it is composed of a finite number of sub-complexes defined in the same way that C'_1 is defined in the paragraph above. The number of these sub-complexes contained in C_1 is obviously an invariant in the sense defined in § 10, for if two complexes C_1 and C'_1 are homeomorphic, any curve on C_1 corresponds to a curve on C'_1 . This number shall be denoted by R_0 . If $R_0 = 1$, C_1 is said to be *connected*.

* No generality is gained by allowing the curves to be singular, but the argument is slightly easier, and more in the spirit of its generalizations to n dimensions.

12. Let us denote the number of 0-cells in a complex C_1 by α_0 and the number of 1-cells by α_1 . The number $\alpha_0 - \alpha_1$ is an invariant.

To prove this, let us first observe that if C_1 be modified by introducing any point of one of its 1-cells as a 0-cell and thereby separating the 1-cell into two 1-cells, the number $\alpha_0 - \alpha_1$ is unchanged. For α_0 is changed to $\alpha_0 + 1$ and α_1 is changed to $\alpha_1 + 1$.

Now consider two linear graphs C_1 and C'_1 between which there is a (1-1) continuous correspondence F . Suppose that C_1 has α_0 0-cells and α_1 1-cells and C'_1 has α'_0 0-cells and α'_1 1-cells. Each 0-cell of C_1 which is an end of only one 1-cell will correspond under F to a 0-cell of C'_1 having the same property; otherwise F could not be continuous. In like manner, each 0-cell of C_1 which is an end of more than two 1-cells will correspond to a 0-cell of C'_1 which is an end of an equal number of 1-cells. For the same reasons, a 0-cell of C'_1 which is an end of only one, or of more than two, 1-cells is the correspondent of a like 0-cell of C_1 .

A certain number of 0-cells of C_1 which are ends of two 1-cells each may correspond to points of C'_1 which are not vertices. Suppose there are k such 0-cells of C_1 and therefore k corresponding points of C'_1 . As explained above, any one of these points of C'_1 may be introduced as a vertex, thereby changing C'_1 into a complex with one more 0-cell and one more 1-cell. Repeating this step k times C'_1 is changed into a complex C''_1 having $\alpha'_0 + k$ 0-cells and $\alpha'_1 + k$ 1-cells. The correspondence F will carry every vertex of C_1 into a vertex of C''_1 .

Certain of the vertices of C''_1 , however, may not be the correspondents under F of vertices of C_1 . Suppose there are n such vertices of C''_1 . By precisely the reasoning used in the last paragraph the points of C_1 which correspond to these n vertices of C''_1 may be introduced as vertices of C_1 , converting C_1 into a complex \bar{C}_1 having $\alpha_0 + n$ 0-cells and $\alpha_1 + n$ 1-cells.

The complexes C''_1 and \bar{C}_1 have been defined so that under the (1-1) correspondence F each vertex of \bar{C}_1 corresponds

to a vertex of C_1'' and each 1-cell of \bar{C}_1 to a 1-cell of C_1'' . Hence

$$\alpha_0 + n = \alpha'_0 + k \quad \text{and} \quad \alpha_1 + n = \alpha'_1 + k,$$

from which it follows that

$$\alpha_0 - \alpha_1 = \alpha'_0 - \alpha'_1.$$

13. The invariant number $\alpha_0 - \alpha_1$ is called the *characteristic** of the linear graph. The number $\alpha_1 - \alpha_0 + R_0$ is called the *cyclomatic number†* and denoted by μ . In the case of a connected complex

$$\mu = \alpha_1 - \alpha_0 + 1.$$

The two invariants, R_0 and $\alpha_0 - \alpha_1$ are evidently not sufficient to characterize a linear graph completely. There is a rather elaborate theory of linear graphs‡ in existence which we shall not attempt to cover. Instead we shall go into detail on questions which cluster around the two invariants already found, because this part of the theory is the basis of important generalizations to n dimensions.

Symbols for Sets of Cells

14. Let us denote the 0-cells of a one-dimensional complex C_1 by $a_1^0, a_2^0, \dots, a_{\alpha_0}^0$ and the 1-cells by $a_1^1, a_2^1, \dots, a_{\alpha_1}^1$.

Any set of 0-cells of C_1 may be denoted by a symbol $(x_1, x_2, \dots, x_{\alpha_0})$ in which $x_i = 1$ if a_i^0 is in the set and $x_i = 0$ if a_i^0 is not in the set. Thus, for example, the pair of points a_1^0, a_4^0 in Fig. 1 is denoted by $(1, 0, 0, 1)$. The total number of symbols $(x_1, x_2, \dots, x_{\alpha_0})$ is 2^{α_0} . Hence the total number of sets of 0-cells, barring the 0-set, is $2^{\alpha_0} - 1$. The symbol for a null-set, $(0, 0, \dots, 0)$ will be referred to as *zero* and denoted by 0.

* Cf. W. Dyck, *Math. Ann.*, Vol. 32, p. 457.

† The term is due to J. B. Listing, *Census räumliche Komplexe*, Göttingen, 1862. But the significance of this constant had been clearly brought out by G. Kirchhoff in the paper referred to in § 36 below.

‡ Cf. Dehn-Heegaard, *Encyklopädie*, III, AB, 3, pp. 172-178.

The marks 0 and 1 which appear in the symbols just defined, may profitably be regarded as residues, modulo 2, i. e., as symbols which may be combined algebraically according to the rules

$$0+0=1+1=0, 0+1=1+0=1, 0 \times 0=0 \times 1=1 \times 0=0, 1 \times 1=1.$$

Under this convention the *sum* (mod 2) of two symbols, or of the two sets of points which correspond to the symbols $(x_1, x_2, \dots, x_{\alpha_0}) = X$ and $(y_1, y_2, \dots, y_{\alpha_0}) = Y$, may be defined as $(x_1 + y_1, x_2 + y_2, \dots, x_{\alpha_0} + y_{\alpha_0}) = X + Y$. Geometrically, $X + Y$ is the set of all points which are in X or in Y but not in both.*

For example, if $X = (1, 0, 0, 1)$ and $Y = (0, 1, 0, 1)$ $X + Y = (1, 1, 0, 0)$; i. e., X represents a_1^0 and a_4^0 , Y represents a_2^0 and a_4^0 , and $X + Y$ represents a_1^0 and a_2^0 . Since a_4^0 appears in both X and Y , it is suppressed in forming the sum, modulo 2.

This type of addition has the obvious property that if two sets contain each an even number of 0-cells, the sum (mod. 2) contains an even number of 0-cells.

15. Any set, S , of 1-cells in C_1 may be denoted by a symbol $(x_1, x_2, \dots, x_{\alpha_1})$ in which $x_i = 1$ if a_i^1 is in the set and $x_i = 0$ if a_i^1 is not in the set. The 1-cells in the set may be thought of as labelled with 1's and those not in the set as labelled with 0's. The symbol is also regarded as representing the one-dimensional complex composed of the 1-cells of S and the 0-cells which bound them. Thus, for example, in Fig. 1 the boundaries of two of the faces are $(1, 0, 1, 0, 1, 0)$ and $(1, 1, 0, 0, 0, 1)$.

The sum (mod. 2) of two symbols $(x_1, x_2, \dots, x_{\alpha_1})$ is defined in the same way as for the case of symbols representing 0-cells. Correspondingly if C_1' and C_1'' are one-dimensional complexes each of which is a sub-complex of a given one-dimensional complex C_1 , the *sum*

* In other words, $X + Y$ is the difference between the logical sum and the logical product of the two sets of points. In terms of the logical operations, if S and S' are the given sets, this one is $S + S' - SS'$.

$$C'_1 + C''_1 \pmod{2}$$

is defined as the one-dimensional complex obtained by suppressing all 1-cells common to C'_1 and C''_1 and retaining all 1-cells which appear only in C'_1 or in C''_1 . For example, in Fig. 1, the sum of the two curves represented by (1, 0, 1, 0, 1, 0) and (1, 1, 0, 0, 0, 1) is (0, 1, 1, 0, 1, 1) which represents the curve, composed of $a_2^1, a_3^1, a_5^1, a_6^1$ and their ends.

The Matrices H_0 and H_1

16. It has been seen in § 11 that any one-dimensional complex falls into R_0 sub-complexes each of which is connected. Let us denote these sub-complexes by $C_1^1, C_1^2, \dots, C_1^{R_0}$, and let the notation be assigned in such a way that a_i^0 ($i=1, 2, \dots, m_1$) are the 0-cells of C_1^1, a_i^0 ($i=m_1+1, \dots, m_2$) those of C_1^2 , and so on.

With this choice of notation, the sets of vertices of $C_1^1, C_1^2, \dots, C_1^{R_0}$, respectively, are represented by the symbols $(x_1, x_2, \dots, x_{\alpha_0})$ which constitute the rows of the following matrix.

$$H_0 = \begin{pmatrix} \overbrace{1 \ 1 \ \dots \ 1}^{m_1} & \overbrace{0 \ 0 \ \dots \ 0}^{m_2 - m_1} & \dots & \overbrace{0 \ 0 \ \dots \ 0}^{\alpha_0 - m_{R_0} - 1} \\ 0 \ 0 \ \dots \ 0 & 1 \ 1 \ \dots \ 1 & \dots & 0 \ 0 \ \dots \ 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 \ 0 \ \dots \ 0 & 0 \ 0 \ \dots \ 0 & \dots & 1 \ 1 \ \dots \ 0 \end{pmatrix} = \|\eta_{ij}^0\|$$

For most purposes it is sufficient to limit attention to connected complexes. In such cases $R_0 = 1$, and H_0 consists of one row all of whose elements are 1.

17. By the definition in § 5 a 0-cell is *incident* with a 1-cell if it is one of the ends of the 1-cell, and under the same conditions the 1-cell is incident with the 0-cell. The incidence relations between the 0-cells and 1-cells may be represented in a table or matrix of α_0 rows and α_1 columns as follows: The 0-cells of C_1 having been denoted by

a_i^0 , ($i = 1, 2, \dots, \alpha_0$) and the 1-cells by a_j^1 , ($j = 1, 2, \dots, \alpha_1$), let the element of the i th row and the j th column of the matrix be 1 if a_i^0 is incident with a_j^1 and let it be 0 if a_i^0 is not incident with a_j^1 .

For example, the table for the linear graph of Fig. 1 formed by the vertices and edges of a tetrahedron is as follows:

	a_1^1	a_2^1	a_3^1	a_4^1	a_5^1	a_6^1
a_1^0	1	0	0	0	1	1
a_2^0	0	1	0	1	0	1
a_3^0	0	0	1	1	1	0
a_4^0	1	1	1	0	0	0

In the case of the complex used in § 5 to define a simple closed curve the incidence matrix is

$$\|\| \begin{matrix} 1 & 1 \\ 1 & 1 \end{matrix} \|\|$$

We shall denote the element of the i th row and j th column of the matrix of incidence relations between the 0-cells and 1-cells by η_{ij}^1 , and the matrix itself by

$$\|\eta_{ij}^1\| = H_1$$

The i th row of H_1 is the symbol for the set of all 1-cells incident with a_i^0 and the j th column is the symbol for the set of two 0-cells incident with a_j^1 .

The condition which we have imposed on the graph, that both ends of every 1-cell shall be among the α_0 0-cells, implies that every column of the matrix contains exactly two 1's. Conversely, any matrix whose elements are 0's and 1's and which is such that each column contains exactly two 1's and each row contains at least one 1, can be regarded as the incidence matrix of a linear graph. For to obtain such a graph it is only necessary to take α_0 points in a 3-space, denote them arbitrarily by $a_1^0, a_2^0, \dots, a_{\alpha_0}^0$, and join the pairs which correspond to 1's in the same column successively by arcs not meeting the arcs previously constructed.

This construction also makes it evident that there is a (1-1) continuous correspondence between any two graphs corresponding to the same matrix H_1 .

Zero-dimensional Circuits

18. A pair of 0-cells is called a *0-dimensional circuit* or a *0-circuit* or a *0-dimensional manifold*. Any even number of 0-cells is a set of 0-circuits and the sum (mod. 2) of any number of 0-circuits is a set of 0-circuits.

If two 0-cells are the ends of an open curve on C_1 (cf. § 5) they are said to *bound* the open curve and *to be connected* by it. Such a pair of 0-cells is called a *bounding 0-circuit*. For example, in Fig. 1, a_1^0 and a_3^0 bound the curve a_3^1 and also bound the curve $a_1^1 a_4^0 a_3^1$.

19. In the symbol $(x_1, x_2, \dots, x_{\alpha_0})$ for a bounding 0-circuit all the x 's are 0 except two which correspond to a pair of vertices belonging to one of the connected complexes into which C_1 falls according to § 11. This symbol must therefore satisfy the following equations,

$$\begin{aligned}
 &x_1 + x_2 + \dots + x_{m_1} = 0, \\
 &x_{m_1+1} + \dots + x_{m_2} = 0, \\
 &\vdots \\
 &x_{m_{p_0-1}+1} + \dots + x_{\alpha_0} = 0,
 \end{aligned}
 \tag{H_0}$$

in which the variables are reduced modulo 2, as explained in § 14. The matrix of these equations is H_0 .

Since the symbol for any set of bounding 0-circuits is the sum (mod. 2) of the symbols for the 0-circuits of the set, it follows that any such symbol satisfies the equations (H_0) . This is also evident because in the symbol for any set of bounding 0-circuits an even number of the x 's in each of these equations must be 1. Hence any such symbol satisfies (H_0) . On the other hand, the symbol for a non-bounding 0-circuit will not satisfy the equations (H_0) because the two x 's which

are not zero in this symbol appear in different equations; and, in general, any set of vertices which is not a set of bounding 0-circuits will contain an odd number of vertices in some connected sub-complex of C_1 , and hence its symbol will fail to satisfy these equations. Hence the set of all solutions of (H_0) is the set of all symbols for sets of bounding 0-circuits.

Since no two of these equations have a variable in common, they are linearly independent. Hence all solutions of (H_0) are linearly dependent (mod. 2) on a set of $\alpha_0 - R_0$ linearly independent solutions.

20. Denoting the connected sub-complexes of C_1 by $C_1^1, C_1^2, \dots, C_1^{R_0}$ as in § 16 let the notation be so assigned that $a_1^1, \dots, a_{m_1}^1$ are the 1-cells in C_1^1 ; $a_{m_1+1}^1, \dots, a_{m_2}^1$ the 1-cells in C_1^2 ; and so on. The matrix H_1 then must take the form

I	0	0	0
0	II	0	0
0	0	III	

where all the non-zero elements are to be found in the matrices I, II, III, etc., and I is the matrix of C_1^1 , II of C_1^2 , etc. This is evident because no element of one of the complexes C_1^i is incident with any element of any of the others.

There are two non-zero elements in each column of H_1 . Hence if we add the rows corresponding to any of the blocks I, II, etc. the sum is zero (mod. 2) in every column. Hence the rows of H_1 are connected by R_0 linear relations.

Any linear combination (mod. 2) of the rows of H_1 corresponds to adding a certain number of them together. If this gave zeros in all the columns it would mean that there were two or no 1's in each column of the matrix formed by the given rows, and this would mean that any 1-cell incident

with one of the 0-cells corresponding to these rows would also be incident with another such 0-cell. These 0-cells and the 1-cells incident with them would therefore form a sub-complex of C_1 which was not connected with any of the remaining 0-cells and 1-cells of C_1 . Hence it would consist of one or more of the complexes C_1^i ($i = 1, 2, \dots, R_0$) and the linear relations with which we started would be dependent on the R_0 relations already found. Hence there are exactly R_0 linearly independent linear relations among the rows of H_1 , so that if ρ_1 is the rank of H_1 ,

$$\rho_1 = \alpha_0 - R_0.$$

It follows that there is a set of $\alpha_0 - R_0$ columns of H_1 upon which all columns are linearly dependent. Since every column of H_1 is a solution of (H_0) and since all solutions of (H_0) are linearly dependent on $\alpha_0 - R_0$ linearly independent solutions, all solutions of (H_0) are linearly dependent on columns of H_1 . In other words *any bounding 0-circuit is the sum of some of the 0-circuits which bound the 1-cells $a_1^1, \dots, a_{\alpha_1}^1$.*

A linearly independent set of solutions of a set of linear equations upon which all other solutions are linearly dependent is called a *complete set* of solutions. Thus a set of ρ_1 linearly independent columns of H_1 forms a complete set of solutions of (H_0) . The corresponding set of 0-circuits is also called a *complete set*.

21. If $R_0 = 1$ the complex C_1 is connected and all its 0-circuits are bounding and expressible linearly (mod. 2) in terms of $\alpha_0 - 1$ of the 0-circuits which bound 1-cells.

In case $R_0 > 1$, a 0-circuit obtained by taking two points, one from each of a pair of the sub-complexes C_1^i ($i = 1, 2, \dots, R_0$) is a non-bounding 0-circuit, while one obtained by taking two points from the same complex C_1^i is bounding.

If $R_0 = 2$ any two 0-cells are both in C_1^1 , or both in C_1^2 , or one in C_1^1 and the other in C_1^2 . A pair of the last type forms a non-bounding 0-circuit and all non-bounding 0-circuits are of this type. If $a_i^0 a_k^0$ is a 0-circuit of the last type any

other non-bounding 0-circuit $a_i^0 a_m^0$ is such that one of its points, say a_i^0 , is in the same connected complex with a_k^0 and the other with a_k^0 . Hence $a_i^0 a_m^0$ is the sum (mod. 2) of $a_i^0 a_k^0$ and the two bounding 0-circuits $a_i^0 a_j^0$ and $a_k^0 a_m^0$. Hence any non-bounding 0-circuit is obtainable by adding bounding 0-circuits to a fixed non-bounding 0-circuit.

By a repetition of this reasoning one finds in the general case that $R_0 - 1$ is the number of non-bounding 0-circuits which must be adjoined to the bounding ones in order to have a set in terms of which all the 0-circuits are linearly expressible (mod. 2). These $R_0 - 1$ non-bounding 0-circuits can obviously be chosen to consist of the pairs of 0-cells, a_1^0, a_i^0 ($i = m_1 + 1, m_2 + 1, \dots, m_{R_0-1} + 1$).

One-dimensional Circuits

22. A connected linear graph each vertex of which is an end of two and only two 1-cells is called a *one-dimensional circuit* or a *1-circuit*. By the theorems of § 5 any closed curve is decomposed by any finite set of points on it into a 1-circuit. Conversely, it is easy to see that the set of all points on a 1-circuit is a simple closed curve. It is obvious, further, that any linear graph, such that each vertex is an end of two and only two 1-cells is either a 1-circuit or a set of 1-circuits no two of which have a point in common.

Consider a linear graph C_1 such that each vertex is an end of an even number of edges. Let us trace a path on C_1 starting at a 0-cell and not covering any 1-cell more than once. As a result of the hypothesis, we must eventually reach some 0-cell for the second time, hence have traced a 1-circuit. We remove this 1-circuit and replace the necessary 0-cells. Since the resulting complex has the property originally assumed for C_1 , it follows that we can repeat the process till there is nothing left. Hence C_1 consists of a number of 1-circuits which have only a finite number of 0-cells in common.

It is obvious that a linear graph composed of a number of closed curves having only a finite number of points in common

has an even number of 1-cells incident with each vertex. Hence a necessary and sufficient condition that C_1 consist of a number of 1-circuits having only 0-cells in common is that each 0-cell of C_1 be incident with an even number of 1-cells. A set of 1-circuits having only 0-cells in common will be referred to briefly as a set of 1-circuits.

23. The sum of the symbols $(x_1, x_2, \dots, x_{\alpha_0})$ for the 0-circuits which bound the 1-cells of a 1-circuit is $(0, 0, \dots, 0)$ because each 0-cell appears in two and only two of these 0-circuits. Hence any 1-circuit or set of 1-circuits determines a linear relation, modulo 2, among the bounding 0-circuits.

Conversely, any linear relation among the 0-circuits which bound 1-cells of a complex determines a 1-circuit or set of 1-circuits. For if the sum of a set of 0-circuits reduces to $(0, 0, \dots, 0)$ each 0-cell must enter in an even number of 0-circuits, i. e., as an end of an even number of 1-cells.

24. Let us now inquire under what circumstances a symbol $(x_1, x_2, \dots, x_{\alpha_1})$ for a one-dimensional complex contained in C_1 will represent a 1-circuit or a system of 1-circuits.

Consider the sum

$$\eta_{i1}^1 x_1 + \eta_{i2}^1 x_2 + \dots + \eta_{i\alpha_1}^1 x_{\alpha_1}$$

where the coefficients η_{ij}^1 are the elements of the i th row of H_1 . Each term $\eta_{ij}^1 x_j$ of this sum is 0 if a_j^1 is not in the set of 1-cells represented by $(x_1, x_2, \dots, x_{\alpha_1})$ because in this case $x_j = 0$; it is also zero if a_j^1 is not incident with a_i^0 because $\eta_{ij}^1 = 0$ in this case. The term $\eta_{ij}^1 x_j = 1$ if a_j^1 is incident with a_i^0 and in the set represented by $(x_1, x_2, \dots, x_{\alpha_1})$ because in this case $\eta_{ij}^1 = 1$ and $x_j = 1$. Hence there are as many non-zero terms in the sum as there are 1-cells represented by $(x_1, x_2, \dots, x_{\alpha_1})$ which are incident with a_i^0 . Hence by § 22 the required condition is that the number of non-zero terms in the sum must be even. In other words if the x 's and η_{ij}^1 's are reduced modulo 2 as explained in § 14 we must have

$$(H_1) \quad \sum_{j=1}^{\alpha_1} \eta_{ij}^1 x_j = 0 \quad (i = 1, 2, \dots, \alpha_0)$$

if and only if $(x_1, x_2, \dots, x_{\alpha_1})$ represents a 1-circuit or set of 1-circuits. The matrix of this set of equations (or congruences, mod. 2) is H_1 .

25. If the rank of the matrix H_1 of the equations (H_1) be ρ_1 the theory of linear homogeneous equations (congruences, mod. 2) tells us that there is a set of $\alpha_1 - \rho_1$ linearly independent solutions of (H_1) upon which all other solutions are linearly dependent. This means geometrically that there exists a set of $\alpha_1 - \rho_1$ 1-circuits or systems of 1-circuits from which all others can be obtained by repeated applications of the operation of adding (mod. 2) described in § 14. We shall call this a complete set of 1-circuits or systems of 1-circuits.

Since $\rho_1 = \alpha_0 - R_0$ (§ 20), the number of solutions of (H_1) in a complete set is

$$\mu = \alpha_1 - \alpha_0 + R_0,$$

where μ is the cyclomatic number defined in § 13. For the sake of uniformity with a notation used later on we shall also denote μ by $R_1 - 1$. Thus we have

$$\alpha_0 - \alpha_1 = 1 + R_0 - R_1.$$

Trees

26. A connected linear graph which contains no 1-circuits is called a tree. As a corollary of the last section it follows that a linear graph is a set of R_0 trees if and only if $\mu = 0$.

Any connected linear graph C_1 can be reduced to a tree by removing μ properly chosen 1-cells. For let a_p^1 ($p = i_1, i_2, \dots, i_{\rho_1}$) be a set of 1-cells whose boundaries form a complete set of 0-circuits (§ 20). The remaining 1-cells of C_1 are μ in number and will be denoted by a_p^1 ($p = j_1, j_2, \dots, j_\mu$). If these μ 1-cells are removed from C_1 the linear graph T_1 which remains is connected because every bounding 0-circuit of C_1 is linearly expressible in terms of the boundaries of the 1-cells a_p^1 ($p = i_1, i_2, \dots, i_{\rho_1}$) of T_1 and hence any two 0-cells of C_1 are joined by a curve composed of 1-cells of T_1 . But since the cyclomatic number of C_1 is $\mu = \alpha_1 - \alpha_0 + 1$,

the removal of μ 1-cells reduces it to 0 and hence reduces C_1 to a tree. In like manner, if C_1 is a linear graph for which $R_0 > 1$, it can be reduced to R_0 trees by removing $\mu = \alpha_1 - \alpha_0 + R_0$ properly chosen 1-cells.

27. There is at least one 1-circuit of C_1 which contains the 1-cell $a_{j_1}^1$, for otherwise C_1 would be separated into two complexes by removing this 1-cell. Call such a 1-circuit C_1^1 . In the complex obtained by removing $a_{j_1}^1$ from C_1 there is, for the same reason, a 1-circuit C_1^2 which contains $a_{j_2}^1$, and so on. Thus there is a set of 1-circuits $C_1^1, C_1^2, \dots, C_1^\mu$ such that C_1^p ($p = 1, 2, \dots, \mu$) contains $a_{j_p}^1$. These 1-circuits are linearly independent because C_1^{k-1} contains a 1-cell, $a_{j_{k-1}}^1$, which does not appear in any of the circuits $C_1^k, C_1^{k-1}, \dots, C_1^1$ and therefore cannot be linearly dependent on them. Hence $C_1^1, C_1^2, \dots, C_1^\mu$ constitute a complete set of 1-circuits. This sharpens the theorem of § 25 a little in that it establishes that there is a complete set of solutions of (H_1) each of which represents a single 1-circuit.

Geometric Interpretation of Matrix Products

28. According to the definition of multiplication of matrices,

$$\|a_{ij}\| \cdot \|b_{jk}\| = \|c_{ik}\|$$

if and only if

$$\sum_{j=1}^{\beta} a_{ij} b_{jk} = c_{ik},$$

β being the number of columns in $\|a_{ij}\|$ and the number of rows in $\|b_{jk}\|$.

Hence, the equations (H_0) of § 19 are equivalent to the matrix equation,

$$H_0 \cdot \begin{pmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_{\alpha_0} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \cdot \\ \cdot \\ 0 \end{pmatrix}.$$

in which the matrix on the right has one column containing R_0 zeros.

Since each column of the matrix H_1 is the symbol (as defined in § 14) for a bounding 0-circuit, (i. e., the j th column is the symbol for the 0-circuit which bounds a_j^1) any column of H_1 is a solution $(x_1, x_2, \dots, x_{\alpha_0})$ of the set of equations (H_0) . By the remark above we may express this result in the form,

$$H_0 \cdot H_1 = 0,$$

where 0 is the symbol for a matrix all of whose elements are zero.

29. By the *boundary* of a one-dimensional complex is meant the set of 0-cells each of which is incident with an odd number of 1-cells of the complex. So, for example, a 1-circuit is a linear graph which has no boundary.

From the definition (§ 14) of addition (mod. 2) of sets of points it is clear that the sum of the boundaries of two 1-cells is the boundary of the complex consisting of the two 1-cells and their ends. By repeated application of this reasoning we prove that the boundary of any one-dimensional complex is an even number of 0-cells, i. e., a number of 0-circuits.

Now consider a one-dimensional complex C'_1 represented by the symbol $(x_1, x_2, \dots, x_{\alpha_1})$ for its 1-cells. According to the reasoning in § 24 each term of

$$\eta_{i1}^1 x_1 + \eta_{i2}^1 x_2 + \dots + \eta_{i\alpha_1}^1 x_{\alpha_1}$$

is 1 or 0 according as the corresponding 1-cell is or is not both in C'_1 and incident with a_i^0 . Hence this expression is 1 or 0 (mod. 2) according as a_i^0 is or is not a boundary point of C'_1 . Hence if we set

$$\eta_{i1}^1 x_1 + \eta_{i2}^1 x_2 + \dots + \eta_{i\alpha_1}^1 x_{\alpha_1} = y_i \quad (i = 1, 2, \dots, \alpha_0)$$

the symbol $(y_1, y_2, \dots, y_{\alpha_0})$ thus determined represents the set of points which bounds C'_1 .

Recalling the rule for multiplying matrices, we see that this result may be stated as follows:

$$H_1 \cdot \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_{\alpha_1} \end{pmatrix} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_{\alpha_0} \end{pmatrix}$$

if and only if $(y_1, y_2, \dots, y_{\alpha_0})$ denotes the set of points which bounds the complex denoted by $(x_1, x_2, \dots, x_{\alpha_1})$.

Reduction of H_0 and H_1 to Normal Form

30. Let us define two matrices B_0 and B_1 as follows:

B_0 is a matrix of α_0 rows and α_0 columns of which the first column is the symbol for a_0^1 , the next $R_0 - 1$ columns are the symbols for the non-bounding 0-circuits enumerated at the end of § 21, and the last $\alpha_0 - R_0$ columns are the symbols for the boundaries of the 1-cells $a_j^1 (j = i_1, i_2, \dots, i_{q_1})$ of the trees of § 26.

B_1 is a matrix of α_1 rows and α_1 columns of which the first q_1 columns are the symbols for $a_j^1 (j = i_1, i_2, \dots, i_{q_1})$, and the last $\alpha_1 - q_1$ columns are the symbols for the 1-circuits $C_1^1, C_2^1, \dots, C_{\mu}^1$.

The determinants of these two matrices are evidently 1 (mod. 2) because the columns of B_0 represent a linearly independent set of 0-dimensional complexes and the columns of B_1 a linearly independent set of 1-dimensional complexes.

The matrix B_0 has the properties: (1) all bounding 0-circuits are linearly dependent (mod. 2) upon the 0-circuits represented by its last q_1 columns; (2) all non-bounding 0-circuits are linearly dependent on its last $\alpha_0 - 1$ columns; (3) all sets of 0-cells are linearly dependent on all its columns.

The matrix B_1 has the properties: (1) all 1-circuits are linearly dependent upon the 1-circuits represented by its last μ columns and (2) all sets of 1-cells are linearly dependent on all its columns.

31. From § 29 and the definition of B_1 it is clear that the first q_1 columns of the product $H_1 \cdot B_1$ must be the symbols

for the boundaries of the 1-cells represented by the first q_1 columns of B_1 . Hence the first q_1 columns of the product $H_1 \cdot B_1$ are the same as the last q_1 columns of B_0 . The remaining columns of $H_1 \cdot B_1$ must be composed entirely of zeros since the remaining columns of B_1 represent 1-circuits. Hence

(1) $H_1 \cdot B_1 = A_0 \cdot H_1^*$,
where

$$H_1^* = \begin{pmatrix} 1 & 0 & \dots & 0 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 & 0 & \dots & 0 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ 0 & 0 & \dots & 1 & 0 & \dots & 0 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ 0 & 0 & \dots & 0 & 0 & \dots & 0 \end{pmatrix}$$

is a matrix of α_0 rows and α_1 columns of which all elements are 0's except the first q_1 elements of the main diagonal, and A_0 is a matrix of α_0 rows and α_0 columns whose first $q_1 = \alpha_0 - R_0$ columns are identical with the last q_1 columns of B_0 and whose last R_0 columns are identical with the first R_0 columns of B_0 . Since the determinant of B_0 is 1, the determinant of A_0 is 1. Hence (1) may be written

(2) $A_0^{-1} \cdot H_1 \cdot B_1 = H_1^*$.

From the point of view of the algebra of matrices (mod. 2) the determination of the two matrices A_0^{-1} and B_1 is the solution of the problem of reducing H_1 to its normal or unitary form, H_1^* . Geometrically (cf. § 30) these matrices may be regarded as summarizing the theory of circuits in a linear graph. It will be found that this geometrical significance of the reduction of H_1 to its normal form generalizes to n dimensions. For the sake of completeness we shall also carry out the analogous reduction of H_0 .

32. From § 28 and the definition of B_0 it is clear that

$$(1) \quad H_0 \cdot B_0 = \begin{vmatrix} 1 & 1 & 1 & \dots & 1 & 0 & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 & 0 & \dots & 0 \\ \cdot & \cdot & \cdot & \dots & \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \cdot & \dots & \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \cdot & \dots & \cdot & \cdot & \dots & \cdot \\ 0 & 0 & 0 & \dots & 1 & 0 & \dots & 0 \end{vmatrix}$$

the right-hand member of this equation being a matrix of R_0 rows and α_0 columns. Each of the first R_0 columns of this matrix contains a 1 for each of the complexes C_1^i ($i = 1, 2, \dots, R_0$) which contains a 0-cell of the set represented by the corresponding columns of B_0 . The last $\alpha_0 - R_0$ columns contain nothing but 0's because the last $\alpha_0 - R_0$ columns of B_0 represent bounding 0-circuits. This equation may also be written in the form

$$(2) \quad H_0 \cdot B_0 = A \cdot H_0^*$$

in which A is a square matrix of R_0 columns identical with the first R_0 columns of $H_0 \cdot B_0$ and H_0^* is a matrix of R_0 rows and α_0 columns all elements of which are 0 except the R_0 elements of the main diagonal, which are all 1.

The determinant of the matrix A is unity and A therefore has a unique inverse A^{-1} . Hence (2) becomes

$$(3) \quad A^{-1} \cdot H_0 \cdot B_0 = H_0^*$$

Thus A^{-1} and B_0 are a pair of matrices by means of which H_0 is transformed to the normal form H_0^* .

Oriented Cells

33. We turn now to the notion of "orientation" or "sense of description" of a complex. The definitions adopted will doubtless seem very artificial, but this is bound to be the case in defining any idea so intuitively elemental as that of "sense."

A 0-cell associated with the number +1 or -1 shall be called an *oriented 0-cell* or *oriented point*.* In the first case

* In analytic applications the number ± 1 associated with a point is usually determined by the sign of a functional determinant.

the oriented 0-cell is said to be *positively oriented* and in the second case it is said to be *negatively oriented*; the two oriented points are called *negatives* of each other. A set of oriented 0-cells is called an *oriented 0-dimensional complex*.

A pair of oriented 0-cells, formed by associating one point of a 0-circuit with +1 and the other with -1 shall be called an *oriented 0-circuit* or an *oriented 0-dimensional manifold*. If a 0-circuit is bounding, any oriented 0-circuit formed from it is also said to be *bounding*.

34. The ends a_1^0, a_2^0 of a 1-cell a^1 when associated each with +1 determine two oriented 0-cells which may be called σ_1^0 and σ_2^0 respectively. Therefore the ends of a^1 determine two oriented 0-circuits, namely $\sigma_1^0, -\sigma_2^0$ and $-\sigma_1^0, \sigma_2^0$. The object formed by associating a^1 with either of these 0-circuits is called an *oriented 1-cell*.

The oriented 1-cell σ^1 formed by associating a^1 with $\sigma_1^0, -\sigma_2^0$ is said to be *positively related* to σ_1^0 and $-\sigma_2^0$ and *negatively related* to $-\sigma_1^0$ and σ_2^0 . An oriented 0-cell is said to be positively or negatively related to an oriented 1-cell according as the 1-cell is positively or negatively related to it.

The point a_1^0 is called the *terminal point* and a_2^0 the *initial point* of the oriented 1-cell σ^1 formed by associating a^1 with $\sigma_1^0, -\sigma_2^0$. In diagrams it is convenient to denote an oriented 1-cell by marking it with an arrow pointing from the initial point to the terminal point.

In the following sections we shall denote the oriented 0-cells obtained by associating each of the 0-cells $a_1^0, a_2^0, \dots, a_{\alpha_0}^0$ of a complex C_1 with +1, by $\sigma_1^0, \sigma_2^0, \dots, \sigma_{\alpha_0}^0$ respectively. We shall also denote an arbitrary one of the two oriented 1-cells which can be formed from a_i^1 ($i = 1, 2, \dots, \alpha_1$) by σ_i^1 . Any set of oriented 1-cells will be called an *oriented one-dimensional complex*. Thus any linear graph can be converted into an oriented complex in 2^{α_1} ways.

35. The cells of a 1-circuit, when oriented by the process described above, give rise to a sequence of oriented 0-cells and 1-cells,

For example, the vertices and edges of the tetrahedron in Fig. 1 when oriented as indicated by the arrows constitute an oriented complex represented by the following matrix:

$$E_1 = \begin{vmatrix} -1 & 0 & 0 & 0 & -1 & 1 \\ 0 & -1 & 0 & 1 & 0 & -1 \\ 0 & 0 & -1 & -1 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \end{vmatrix}$$

39. Each column of the matrix E_1 is the symbol (§ 37) for a bounding oriented 0-circuit and hence is a solution of the set of equations (E_0). In the notation of matrices, this means

$$(1) \quad E_0 \cdot E_1 = 0.$$

The matrix E_1 falls into a set of matrices I, II, III, etc. corresponding to those into which H_1 is decomposed in § 20. The sum of the rows of any one of these matrices I, II, III is zero because each column has one +1 and one -1. On the other hand the rows of such a matrix, say I, cannot be subject to any other linear relation because one of the variables could be eliminated between this relation and the one which states that the sum of the rows is zero, and the resulting relation, after its coefficients were divided by their H. C. F. and then reduced modulo 2, would give a linear relation among the rows of H_1 of a type which has been shown in § 20 to be non-existent. Hence the rows of E_1 are subject to R_0 linearly independent linear relations. Hence if r_1 denote the rank of E_1 ,

$$r_1 = \rho_1 = \alpha_0 - R_0.$$

40. The form of the matrices E_0 and E_1 has been limited somewhat by the convention that $\sigma_1^0, \sigma_2^0, \dots, \sigma_{\alpha_0}^0$ denote 0-cells each associated with +1. If we interchange the significance of σ_i^0 and $-\sigma_i^0$, so that σ_i^0 represents α_i^0 associated with -1. it is necessary to change the 1 in the i th column of E_0 to -1 and to make corresponding changes in the columns of E_1 .

The rest of the discussion on this slightly more general foundation does not differ in essentials from that already given.

Oriented 1-Circuits

41. Every oriented 1-circuit corresponds to a linear relation among the oriented 0-circuits which bound the oriented 1-cells of which it is composed, for if a given oriented 0-cell is positively related to one such oriented 1-cell, its negative is, by the terms of the definition, positively related to another oriented 1-cell of the oriented 1-circuit. Conversely any linear relation among the bounding 0-circuits determines an oriented 1-circuit or set of oriented 1-circuits. All this is analogous to § 23. Taken with § 39 it establishes that the number of linearly independent linear relations among bounding oriented 0-circuits is the same as among bounding 0-circuits when reduced modulo 2.

42. Any set of oriented 1-cells of a complex C_1 may be denoted by $(x_1, x_2, \dots, x_{\alpha_1})$ where $x_i = 1$ if σ_i^1 is in the set, $x_i = -1$ if $-\sigma_i^1$ is in the set, and $x_i = 0$ if neither σ_i^1 nor $-\sigma_i^1$ is in it. A necessary and sufficient condition that such a symbol represent an oriented 1-circuit or set of oriented 1-circuits is that it satisfy the system of equations,

$$(E_1) \quad \sum_{j=1}^{\alpha_1} \epsilon_{ij}^1 x_j = 0 \quad (i = 1, 2, \dots, \alpha_0),$$

the matrix of which is E_1 . For in this set, the equation,

$$(1) \quad \epsilon_{i1}^1 x_1 + \epsilon_{i2}^1 x_2 + \dots + \epsilon_{i\alpha_1}^1 x_{\alpha_1} = 0$$

corresponds to the oriented 0-cell σ_i^0 . A term $\epsilon_{ij}^1 x_j$ of the left member is zero if $\epsilon_{ij}^1 = 0$ or if $x_j = 0$, that is, if σ_i^1 is not an end of σ_j^1 or if the set of oriented 1-cells does not contain $\pm \sigma_j^1$. The term $\epsilon_{ij}^1 x_j$ is +1 if ϵ_{ij}^1 and x_j are of the same sign, that is if the set of oriented 1-cells contains σ_j^1 and the latter is positively related to σ_i^0 or if it contains $-\sigma_j^1$ and $-\sigma_j^1$ is positively related to σ_i^0 ; hence there are as many +1 terms in the left member of (1) as there are oriented 1-cells

in the set $(x_1, x_2, \dots, x_{\alpha_1})$ which are positively related to σ_i^0 . In like manner there are as many -1 terms as there are oriented 1-cells in the set which are negatively related to σ_i^0 . Hence the left-hand member of (1) is the difference between the number of oriented 1-cells in the set which are positively related to σ_i^0 and the number which are negatively related to σ_i^0 . Hence an oriented 1-circuit satisfies the equations (E_1) , and any solution of (E_1) of the kind in question must represent an oriented 1-circuit or a set of oriented 1-circuits.

Since the number of variables x_j in the equations (E_1) is α_1 and the rank of the matrix of coefficients is $\alpha_0 - R_0$ (cf. § 39) the number of solutions in a set on which all others are linearly dependent is μ where

$$\mu = \alpha_1 - \alpha_0 + R_0.$$

Such a set is obviously obtained by converting the μ 1-circuits of § 27 into oriented 1-circuits. The symbols $(x_1, x_2, \dots, x_{\alpha_1})$ for these 1-circuits are linearly independent solutions of (E_1) in which the x 's are 0 or ± 1 .

It is obvious that the equations (E_1) have solutions in which the x 's are integers different from 0 and ± 1 . In order to interpret these solutions we shall return to the notion of a singular complex on C_1 (§ 8).

Symbols for Oriented Complexes

43. If a 0-cell \bar{a}^0 on C_1 (in the sense of § 7) is associated with $+1$ or -1 the resulting oriented 0-cell $\bar{\sigma}^0$ is said to be on C_1 , and if \bar{a}^0 coincides with a 0-cell a_i^0 of C_1 , $\bar{\sigma}^0$ is said to coincide with σ_i^0 or $-\sigma_i^0$ according as $\bar{\sigma}^0$ is positively or negatively oriented.

Let C'_1 be any linear graph on C_1 such that each 1-cell of C'_1 covers a 1-cell of C_1 just once (cf. § 9). If the cells of both complexes are oriented, an oriented 1-cell σ'_p of C'_1 will be said to coincide with an oriented 1-cell σ_q of C_1 if and only if (1) each point of σ'_p coincides with a point of σ_q and (2) each oriented 0-cell of C'_1 is positively or negatively

related to σ_p according as it coincides with an oriented 0-cell of C_1 which is positively or negatively related to σ_q .

44. A symbol $(x_1, x_2, \dots, x_{\alpha_1})$ in which the x 's are positive or negative integers or 0 will be taken to represent a set of oriented i -cells ($i = 0$ or 1) on C_1 in which (1) if x_j ($j = 1, 2, \dots, \alpha_1$) is positive there are x_j oriented i -cells coinciding with σ_j^i , (2) if x_j is negative there are $-x_j$ oriented i -cells coinciding with $-\sigma_j^i$, and (3) if $x_j = 0$ there are no oriented i -cells coinciding with σ_j^i or $-\sigma_j^i$.

The object obtained by assigning orientations to the 1-cells of a complex is called an oriented 1-dimensional complex. A singular oriented complex is defined in similar manner. A singular oriented complex whose cells coincide with cells of C_1 determines a symbol $(x_1, x_2, \dots, x_{\alpha_1})$. Conversely, any such symbol determines at least one oriented complex having that symbol for its oriented 1-cells. This complex can in general be constructed in a variety of ways, depending on how we join the 1-cells by 0-cells.

In case the numbers x_j ($j = 1, 2, \dots, \alpha_1; i = 0, 1$), have a common factor different from unity, i. e., in case

$$(x_1, x_2, \dots, x_{\alpha_1}) = (z_1 d, z_2 d, \dots, z_{\alpha_1} d),$$

any oriented complex whose symbol is $(z_1, z_2, \dots, z_{\alpha_1})$ is said to be covered d times by a complex with symbol $(x_1, x_2, \dots, x_{\alpha_1})$ formed by orienting the cells of a complex covering $(z_1, z_2, \dots, z_{\alpha_1})$ d times in the sense of § 9.

45. If $(x_1, x_2, \dots, x_{\alpha_1})$ and $(y_1, y_2, \dots, y_{\alpha_1})$ are symbols for two sets of oriented i -cells ($i = 0, 1$), the symbol $(x_1 + y_1, x_2 + y_2, \dots, x_{\alpha_1} + y_{\alpha_1})$ is called the sum of the two symbols and the set of oriented i -cells which it represents is called the sum of the two sets of oriented i -cells.

Given two (singular) oriented complexes, any oriented complex whose symbol is the sum of the symbols of the given complexes is called a sum of those complexes.

For example, in Fig. 1 the oriented 1-circuit composed of $\sigma_4^1, \sigma_5^1, \sigma_6^1$ may be denoted by $(0, 0, 0, 1, 1, 1)$ and the oriented 1-circuit composed of $\sigma_2^1, \sigma_1^1, -\sigma_3^1$ may be denoted by $(0, 1,$

$-1, 1, 0, 0$). Their sum is $(0, 1, -1, 2, 1, 1)$. If each of σ_2^1, σ_4^1 and $-\sigma_3^1$ be replaced by its negative the sum becomes $(0, -1, 1, 0, 1, 1)$. In the first case the sum determines a pair of oriented 1-circuits, σ_4^1 appearing once in each; in the second case the sum determines a single oriented 1-circuit.

It can be proved by an argument analogous to that used in § 22 that any solution of the equations (E_1) represents a set of oriented 1-circuits, two or more of which may have a given oriented 1-cell in common.

46. By the *boundary* of an oriented 1-cell is meant the pair of oriented points which are positively related to it. By the *boundary* of any oriented one-dimensional complex is meant the sum of the boundaries of the oriented 1-cells composing it.

From this definition it follows directly that an oriented 1-circuit has no boundary and that any set of oriented 1-cells without a boundary may be regarded as a set of 1-circuits.

If $(x_1, x_2, \dots, x_{\alpha_1})$ is the symbol for a single oriented 1-cell, it is obvious from the reasoning used in § 42 that $(y_1, y_2, \dots, y_{\alpha_0})$ is the symbol for its boundary if and only if

$$(1) \quad E_1 \cdot \begin{vmatrix} x_1 \\ x_2 \\ \vdots \\ x_{\alpha_1} \end{vmatrix} = \begin{vmatrix} y_1 \\ y_2 \\ \vdots \\ y_{\alpha_0} \end{vmatrix}.$$

But the most general symbol $(x_1, x_2, \dots, x_{\alpha_1})$ in which the x 's are integers or zero can be expressed as a sum of symbols for oriented 1-cells, and by the algebraic properties of matrices.

$$(2) \quad E_1 \cdot \begin{vmatrix} x_1 + x'_1 \\ x_2 + x'_2 \\ \vdots \\ x_{\alpha_1} + x'_{\alpha_1} \end{vmatrix} = E_1 \cdot \begin{vmatrix} x_1 \\ x_2 \\ \vdots \\ x_{\alpha_1} \end{vmatrix} + E_1 \cdot \begin{vmatrix} x'_1 \\ x'_2 \\ \vdots \\ x'_{\alpha_1} \end{vmatrix}.$$

Hence in the general case, $(y_1, y_2, \dots, y_{\alpha_0})$ is the symbol for the boundary of $(x_1, x_2, \dots, x_{\alpha_1})$ if and only if (1) is satisfied.

Normal Form for E_0

47. All columns, except the first one, of the matrix B_0 which appeared (§ 32) in the reduction of H_0 to normal form are symbols for 0-circuits. Hence by changing one of the 1's in each column after the first column to -1 , B_0 is converted into a matrix, D_0 , of which the first column represents the oriented 0-cell σ_1^0 , the next $R_0 - 1$ columns represent linearly independent non-bounding oriented 0-circuits, and the last $\alpha_0 - R_0$ columns represent linearly independent bounding oriented 0-circuits. The product $E_0 \cdot D_0$ is clearly obtained from $H_0 \cdot B_0$ by changing one 1 to -1 in each column from the second to the R_0 th. Hence

$$(1) \quad E_0 \cdot D_0 = C \cdot E_0^*,$$

where E_0^* is the same as H_0^* and C is obtained from A by changing one 1 into -1 in each column except the first. The determinant of C is ± 1 . Hence there exists a matrix C^{-1} whose elements are integers and (1) can be written in the form

$$(2) \quad C^{-1} \cdot E_0 \cdot D_0 = E_0^*.$$

The reduction of E_0 to normal form, therefore, is completely parallel to the corresponding reduction of H_0 .

Matrices of Integers

48. The reduction of E_1 to normal form can be obtained directly from the general theory of matrices whose elements are integers.* The fundamental theorem of this theory is that for any matrix E of α_1 rows and α_2 columns whose elements are integers there exist two square matrices C and

* The part of this theory which is needed for our purposes is the subject of an expository article (Appendix II) by P. Franklin and the author in the *Annals of Mathematics*, Vol. 23 (1921), pp. 1-15.

D of α_1 rows and α_2 rows respectively, each of determinant ± 1 , such that

$$(1) \quad C \cdot E \cdot D = E^*$$

where E^* is a matrix of α_1 rows and α_2 columns

$$E^* = \begin{vmatrix} d_1 & 0 & \dots & 0 & \dots & 0 \\ 0 & d_2 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & & \vdots & & \vdots \\ 0 & 0 & \dots & d_r & \dots & 0 \\ \vdots & \vdots & & \vdots & & \vdots \\ 0 & 0 & \dots & 0 & \dots & 0 \end{vmatrix}$$

in which d_1 is the highest common factor of all the elements of E , $d_1 d_2$ the H.C.F. of all the two-rowed determinants which can be found by removing rows and columns from E , and finally, $d_1 d_2 \dots d_r$ the H.C.F. of all the r -rowed determinants which can be formed from E . The number d_1 is the H.C.F. of all the numbers $d_1 d_2 d_3 \dots d_r$, d_2 is the H.C.F. of d_2, d_3, \dots, d_r , etc.

The numbers d_1, d_2, \dots, d_r are called the *invariant factors*, or the *elementary divisors* of the matrix E . They are invariants in the sense that if E is multiplied on the left by a square matrix of α_1 rows and determinant ± 1 and on the right by any square matrix of α_2 rows and determinant ± 1 , the resulting matrix will be such that the H.C.F. of all the k -rowed determinants which can be formed from it is $d_1 \cdot d_2 \cdot \dots \cdot d_k$ ($k = 1, 2, \dots, r$).

If all elements be reduced modulo 2, E reduces to a matrix H all of whose elements are 0 or 1. The equation (1) reduces to an equation like (2) of § 31. The rank of E differs from the rank of H by the number of d 's which contain 2 as a factor.

Normal Form for E_1

49. Suppose we apply the theory just described to the reduction to normal form of the matrix E_1 , with the reduction represented by the equation

$$(1) \quad C_0^{-1} \cdot E_1 \cdot D_1 = E_1^*.$$

From this we get the following result: There exists a *complete set* of sets of 1-circuits, that is, one such that an arbitrary set of 1-circuits is a linear combination, with integral coefficients, of its members. To prove this, we first obtain from (1) the relation,

$$(2) \quad E_1 \cdot D_1 = C_0 \cdot E_1^*.$$

Since the last $\alpha_1 - r_1$ columns of E_1^* are composed of zeros, the last $\alpha_1 - r_1$ columns of D_1 represent sets of 1-circuits, which must be independent, since the determinant of D_1 is not zero. Since the determinant of D_1 is actually ± 1 , an arbitrary set of 1-circuits must be uniquely expressible as a linear combination, with integral coefficients, of the complexes represented by the columns of D_1 . If this linear combination actually involved any of the first r_1 columns, the combination of the latter columns in question must represent a set of 1-circuits, and also be independent of the last $\alpha_1 - r_1$ columns, as all the columns of D_1 are linearly independent. Hence the equations (E_1) would have more than $\alpha_1 - r_1$ linearly independent solutions, which we know is not the case. Therefore the linear combination in question cannot involve any of the first r_1 columns, and we conclude that the last $\alpha_1 - r_1$ columns represent a complete set of sets of 1-circuits.

50. We shall now outline a proof of the fact that the invariant factors of E_1 are all $+1$. Suppose a certain invariant factor, say the j th, had a value greater than 1, say d . Then from (2) it follows that the j th column of C_0 would represent a set of 0-circuits which, taken d times, would bound a 1-dimensional complex represented by the j th column of D_1 . When we go into the subject more deeply, in the general case (Chap. IV, § 30), we shall prove that under these conditions the set of 0-circuits in question could not bound when taken a smaller positive number of times than d . But it is not difficult to prove that if a set of

0-circuits bounds when taken d times, d positive, then it also bounds when taken once. Hence the existence of the invariant factor d would lead us to a contradiction; and it follows that all the invariant factors of E_1 are 1.

51. In view of the general theory it is seen that the matrix E_1 for a linear graph is characterized by the fact that *its invariant factors are all +1*. On this account the theory of the matrix E_1 is essentially the same as that of H_1 . When we come to the generalizations to two and more dimensions, the invariant factors of the matrix will no longer have this simple property and the invariant factors will turn out to be important Analysis Situs invariants.

CHAPTER II

TWO-DIMENSIONAL COMPLEXES AND MANIFOLDS

Fundamental Definitions

1. In a Euclidean space three non-collinear points and the segments which join them by pairs constitute the boundary of a finite region in the plane of the three points. This region is called a *triangular region* or *two-dimensional simplex* and the three given points are called its *vertices*. The points of the boundary are not regarded as points of the region.

Consider any set of objects in (1-1) correspondence with the points of a two-dimensional simplex and its boundary. The objects corresponding to the points of the simplex constitute what is called a *two-dimensional cell* or *2-cell*, and those corresponding to the boundary of the simplex what is called the *boundary of the 2-cell*.

The objects which constitute a cell and its boundary will hereafter be referred to as "points," and the remarks in § 2, Chap. I, with regard to order relations are carried over without change to the two-dimensional case. The boundary of a 2-cell obviously satisfies the definition given in Chap. I of a closed curve.

2. A *two-dimensional complex* may be defined as a one-dimensional complex C_1 together with a number, α_2 , of 2-cells whose boundaries are 1-circuits of the one-dimensional complex, such that each 1-cell is on the boundary of at least one 2-cell and no 2-cell has a point in common with another 2-cell or with C_1 . The order relations of the points of the boundary of each 2-cell must coincide with the order relations determined among these points as points of the 1-circuit of the one-dimensional complex which coincides with the boundary. (Compare the footnote to § 2, Chap. III.)

The surface of a tetrahedron (cf. Fig. 1) is a simple example of a two-dimensional complex. Any polyhedron or combination of polyhedra in a Euclidean space will furnish a more complicated example.

An arbitrary subset of the 0-cells, 1-cells, and 2-cells of a two-dimensional complex will be occasionally referred to as a *generalized two-dimensional complex*.

3. The definitions of limit point and continuous transformation given in Chap. I may be generalized directly to two-dimensional complexes and we take them for granted without further discussion. As in § 4, Chap. I, two complexes are said to be *homeomorphic* if there exists a (1-1) continuous correspondence between them; and any such correspondence is called a *homeomorphism*. The two complexes will in general be defined in quite different ways so that the numbers $\alpha_0, \alpha_1, \alpha_2$ are different; but if the two complexes are homeomorphic there is a (1-1) continuous correspondence between them as sets of points.

Any proposition about a complex or set of complexes which is unaltered under the group of all homeomorphisms of these complexes is called a proposition of *two-dimensional Analysis Situs*.

Matrices of Incidence

4. The 0-cells and 1-cells on the boundary of a 2-cell are said to be *incident* with the 2-cell and the 2-cell to be *incident* with the 0-cells and 1-cells of its boundary. The incidence relations between the 1-cells and 2-cells of a two-dimensional complex C_2 may be indicated by a table or matrix analogous to that described in § 17, Chap. I. The 2-cells, α_2 in number, shall be denoted by $\alpha_1^2, \alpha_2^2, \dots, \alpha_{\alpha_2}^2$. The matrix $H_2 = \|\eta_{ij}^2\|$ which describes the incidence relations between the 1-cells and 2-cells is such that $\eta_{ij}^2 = 0$ if α_i^1 is not incident with α_j^2 and $\eta_{ij}^2 = 1$ if α_i^1 is incident with α_j^2 .

In the case of the tetrahedron in Fig. 1, let us denote the 2-cells opposite the vertices $\alpha_1^0, \alpha_2^0, \alpha_3^0, \alpha_4^0$ by $\alpha_1^2, \alpha_2^2, \alpha_3^2, \alpha_4^2$ respectively. The table of incidence relations becomes

	α_1^2	α_2^2	α_3^2	α_4^2
α_1^1	0	1	1	0
α_2^1	1	0	1	0
α_3^1	1	1	0	0
α_4^1	1	0	0	1
α_5^1	0	1	0	1
α_6^1	0	0	1	1

5. Since each column of H_2 contains α_1 elements it may be regarded as a symbol $(x_1, x_2, \dots, x_{\alpha_1})$ in the sense of § 15, Chap. I for a set of 1-cells. The j th column of H_2 is, in fact the symbol for the 1-cells on the boundary of the 2-cell α_j^2 . It is therefore the symbol for a 1-circuit. Hence the columns of H_2 are solutions of the equations (H_1) . That is to say

$$\sum_{j=1}^{\alpha_1} \eta_{ij}^1 \eta_{jk}^2 = 0 \quad (i = 1, \dots, \alpha_0, k = 1, \dots, \alpha_2)$$

or, in terms of the multiplication of matrices,

$$(1) \quad H_1 \cdot H_2 = 0,$$

where 0 stands for the matrix all of whose elements are zero.

It should be recalled here that we have already proved in § 28, Chap. I that

$$H_0 \cdot H_1 = 0.$$

The ranks of the matrices H_0, H_1, H_2 , computed modulo 2, will be denoted by $\varrho_0, \varrho_1, \varrho_2$ respectively.

6. From the point of view of Analysis Situs a two-dimensional complex is fully described by the three matrices H_0, H_1, H_2 for there is no difficulty in proving that if two two-dimensional complexes have the same matrices there is a (1-1) continuous correspondence between them. Our definitions are such that the boundary of every 1-cell is a pair of distinct points and the boundary of every 2-cell a non-singular curve. Hence a figure composed of a 1-cell incident with a 0-cell or a 2-cell is in (1-1) continuous correspondence with any other such figure.

If two complexes C_2 and \bar{C}_2 have the same matrices their 0-cells, 1-cells and 2-cells may be denoted by a_i^0, a_j^1, a_k^2 and b_i^0, b_j^1, b_k^2 in such a way that whenever a_j^1 for any values of i, j, k is incident with a_i^0 or a_k^2 , the b_j^1 for the same value of j is incident with the b_i^0 or b_k^2 with the same value of i or k . A (1-1) continuous correspondence is then set up between C_2 and \bar{C}_2 by requiring: (1) that a_i^0 correspond to b_i^0 for each value of i , (2) that a_j^1 and its ends correspond to b_j^1 and its ends for each value of j in a (1-1) continuous correspondence such that the correspondence between the ends is that set up under (1), and (3) that a_k^2 and its boundary correspond to b_k^2 and its boundary in a (1-1) continuous correspondence by which the boundaries correspond in the correspondence set up under (2).

Subdivision of 2-Cells

7. The properties of a two-dimensional complex will be obtained by studying the combinatorial relations codified in the matrices H_0, H_1, H_2 in connection with the continuity properties of the 2-cell. The latter properties, according to the definition in § 1, depend on the order relations in a Euclidean plane and, in particular, on the theory of planar polygons. The theory of polygons can be built up in terms of the incidence matrices. For consider a set of n straight lines in a Euclidean plane. They separate it into a number α_2 of planar convex regions and intersect in a number α_0 of points which divide the lines into a number α_1 of linear convex regions. The α_0 points can be treated as 0-cells, the α_1 linear convex regions as 1-cells and the α_2 planar convex regions as 2-cells. Any polygon is a 1-circuit, and the theory of linear dependence as developed in our first chapter can be applied to the proof of the fundamental theorems on polygons. For the details of this theory, which belongs to affine geometry rather than to Analysis Situs, the reader is referred to Chapters II and IX of the second volume of Veblen and Young's Projective Geometry.

8. The (1-1) correspondence with the interior and boundary of a triangle which defines a 2-cell and its boundary determines a system of 1-cells in the 2-cell which are the correspondents of the straight 1-cells in the interior of the triangle. By regarding this system of 1-cells as the *straight 1-cells* and defining the *distance* between any two points of the 2-cell and its boundary as the distance between the corresponding two points of the interior of the triangle, we can carry over all the theorems of the elementary geometry of a triangle to the 2-cell. The notions of distance and straightness so developed, however, are not invariant under the group of homeomorphisms, and the corresponding theorems are not theorems of Analysis Situs. For purposes of Analysis Situs the theorem of interest here is simply that there exists a system of 1-cells which are in (1-1) continuous correspondence with the straight 1-cells of the interior of a triangle of the Euclidean plane.

Given two circles in a Euclidean plane, it is a simple matter to put them and their interiors in (1-1) continuous correspondence in such a way that the correspondence thus set up between the circles is any preassigned homeomorphism. It follows that if definitions of distance are assigned arbitrarily along all the 1-cells of any complex C_2 , definitions of distance and straightness can then be assigned to the 2-cells and their boundaries in such a way that the distances thus assigned along the 1-cells agree with those previously assigned. If a 2-cell has only two 1-cells on its boundary, they are necessarily curved under the definitions of distance and straightness for that 2-cell. Otherwise they can be taken straight.

9. The following theorems follow immediately from the homeomorphism between a 2-cell and the triangle used in defining it:

If two points A and B of the boundary of a 2-cell a^2 are joined by a straight 1-cell a^1 consisting of points of a^2 , the remaining points of a^2 constitute two 2-cells each of which is bounded by a^1, A, B and one of the two 1-cells into which the boundary of a^2 is divided by A and B .

If the boundaries of two 2-cells a_1^2 and a_2^2 have a 1-cell a^1 and its ends in common, and the 2-cells and their boundaries have no other common points, then a_1, a_1^1 and a_2^2 constitute a 2-cell.

If there is a (1-1) continuous correspondence F' between the boundaries of two 2-cells a_1^2 and a_2^2 , there exists a (1-1) continuous correspondence F between the interior and boundary of a_1^2 and the interior and boundary of a_2^2 which effects the correspondence F' between the boundaries.

A point of a 2-cell can be joined to a set of points A_1, A_2, \dots, A_n of its boundary by a set of 1-cells $a_1^1, a_2^1, \dots, a_n^1$ which are in the 2-cell and have no points in common. The 2-cell is thus decomposed into n 2-cells $a_1^2, a_2^2, \dots, a_n^2$ such that the sum of their boundaries (mod. 2) is the boundary of a^2 and such that the incidence relations between them and $a_1^1, a_2^1, \dots, a_n^1$ are the same as the incidence relations between the 0-cells and 1-cells of a 1-circuit.

Conversely, if $a_1^1, a_2^1, \dots, a_n^1$ and $a_1^2, a_2^2, \dots, a_n^2$ are 1-cells and 2-cells all incident with the same point a^0 and also incident with one another in such a way that the incidence relations between the 1-cells and 2-cells are the same as those between the 0-cells and 1-cells of a 1-circuit, and $a_1^1, a_2^1, \dots, a_n^1$ are the only 1-cells that the boundaries of any two of the 2-cells $a_1^2, a_2^2, \dots, a_n^2$ have in common, then the point a^0 and the points of $a_1^1, a_2^1, \dots, a_n^1$ and $a_1^2, a_2^2, \dots, a_n^2$ constitute a 2-cell a^2 which is bounded by the sum (mod. 2) of the boundaries of the 2-cells $a_1^2, a_2^2, \dots, a_n^2$.

10. The first of the theorems in the last section is a special case of the theorem that any 1-cell which is in a 2-cell and joins two points of its boundary decomposes the 2-cell into two 2-cells. This more general theorem depends on the theorem of Jordan, that any simple closed curve in a Euclidean plane separates the plane into two regions, the interior and the exterior; and also on the theorem of Schoenflies that the interior of a simple closed curve is a 2-cell of which the curve is the boundary.

We shall not need to use these more general forms of the separation theorems because we need, in general, merely the

existence of curves which separate cells, and this is provided for in the theorems of the last section. In connection with the Jordan theorem, reference may be made to the proof by J. W. Alexander, *Annals of Mathematics*, Vol. 21 (1920), p. 180.

Maps

11. With the aid of the theorems on separation a 2-cell a^2 may be subdivided into further 2-cells as follows: Let any two points a_1^0 and a_2^0 of the boundary of the 2-cell be joined by a straight 1-cell a_1^1 consisting entirely of points of the 2-cell. The 2-cell is thus separated into two 2-cells a_1^2 and a_2^2 . The boundary of a^2 is likewise separated into two 1-cells a_1^1 and a_2^1 which have a_1^0 and a_2^0 as ends. The 0-cells, 1-cells and 2-cells into which a^2 is thus subdivided constitute a 2-dimensional complex C_2 whose matrices are

$$H_0 = \begin{vmatrix} 1 & 1 \end{vmatrix}, \quad H_1 = \begin{vmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{vmatrix}, \quad H_2 = \begin{vmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{vmatrix}.$$

The numbers $\alpha_0, \alpha_1, \alpha_2$ for C_2 are respectively 2, 3, 2, so that

$$\alpha_0 - \alpha_1 + \alpha_2 = 1.$$

This subdivision of a^2 may be continued by two processes: (1) introducing a point of a 1-cell as a new 0-cell and (2) joining two 0-cells of the boundary of a 2-cell by a 1-cell composed entirely of points of the 2-cell. The first process increases the numbers of 0-cells and 1-cells each by 1. The second process increases the numbers of 1-cells and 2-cells each by 1. Hence any number of repetitions of the two processes leave the number $\alpha_0 - \alpha_1 + \alpha_2$ invariant.

Any two-dimensional complex obtainable from a 2-cell by subdivision of the kind described above is called a *simply connected map*; and it can easily be proved that any two-dimensional complex which is homeomorphic with the interior and boundary of a 2-cell is a simply connected map.

The number $\alpha_0 - \alpha_1 + \alpha_2$ determined by any complex C_2 having α_0 0-cells, α_1 1-cells and α_2 2-cells is called the *character-*

istic of C_2 . Thus we have proved that *the characteristic of a simply connected map is 1.*

12. There are a number of interesting theorems about simply connected maps which must be omitted here because they are of too special a nature. Many of them are related to the *four color problem*: is it possible to color the cells of a simply connected map with four colors in such a way that no two 2-cells which are incident with the same 1-cell are colored alike? This problem is still unsolved, in spite of numerous attempts. In addition to the references in the Encyclopädie, Vol. III, p. 177, the following references may be cited: Birkhoff, *The reducibility of maps*, American Journal of Mathematics, Vol. 35, p. 115; Veblen, *Annals of Mathematics*, Vol. 14 (1912), p. 86; and an article by P. Franklin in the American Journal, Vol. 44 (1922), pp. 225-236.

Regular Subdivision

13. It will often be found convenient to work with complexes whose 2-cells are each incident with three 0-cells and three 1-cells. Such 2-cells will be called *triangles* and a complex subdivided into triangles will be said to be *triangulated*. Any complex C_2 may be triangulated by the following process which is called a *regular subdivision*.

Let P_k^2 ($k = 1, 2, \dots, \alpha_2$) be an arbitrary point of the 2-cell a_k^2 , P_j^1 ($j = 1, 2, \dots, \alpha_1$) an arbitrary point of the 1-cell a_j^1 and P_i^0 ($i = 1, 2, \dots, \alpha_0$) another name for the 0-cell a_i^0 . The points P_j^i ($i = 0, 1, 2; j = 1, 2, \dots, \alpha_i$) are to be the vertices of the complex \bar{C}_2 .

Each P_j^1 separates the a_j^1 on which it lies into two 1-cells. The 1-cells so defined are to be among the 1-cells of \bar{C}_2 . The remaining 1-cells of \bar{C}_2 are obtained by joining each P_k^2 to each of the points P_i^0 and P_j^1 of the boundary of a_k^2 by a straight 1-cell in a_k^2 . Each 2-cell a_k^2 is thus decomposed into a set of 2-cells each of which is bounded by three of the 1-cells of \bar{C}_2 , one on the boundary of a_k^2 and two interior to a_k^2 . The 2-cells thus obtained are the 2-cells of \bar{C}_2 .

The complex \bar{C}_2 is called a *regular subdivision* of C_2 , and is also called a *regular complex*. No two 0-cells of \bar{C}_2 are joined by more than one 1-cell of \bar{C}_2 . Moreover no 1-cell of \bar{C}_2 joins two points P_k^i, P_l^i which have equal superscripts. Hence any 1-cell of \bar{C}_2 may be denoted by $P_k^i P_l^j$ with $i < j$.

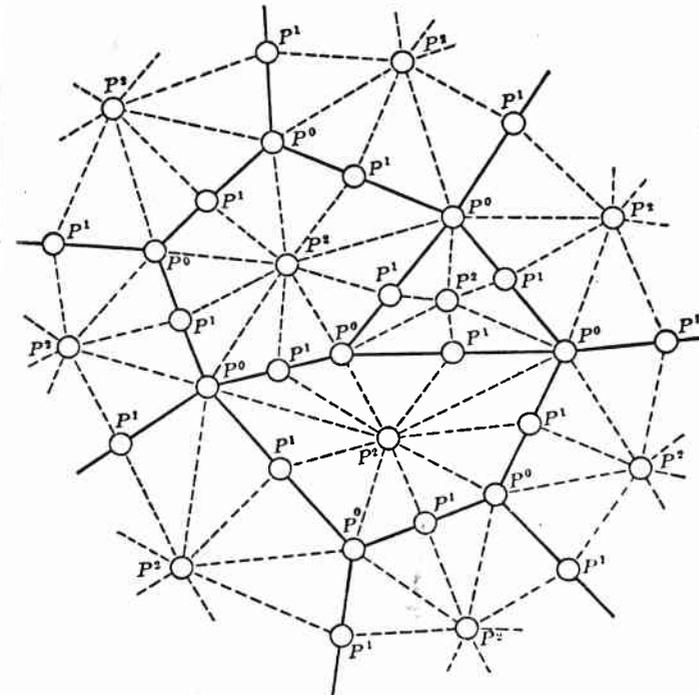


FIG. 3.

No three 0-cells of \bar{C}_2 are vertices of more than one 2-cell of \bar{C}_2 , and furthermore one of the three vertices incident with any 2-cell is a P_i^0 , one is a P_j^1 , and one is a P_k^2 . Hence any 2-cell of \bar{C}_2 may be denoted by $P_i^0 P_j^1 P_k^2$.

14. Any vertex of \bar{C}_2 together with the 1-cells and 2-cells which are incident with it is called a *triangle star*, and the vertex is called the *center* of the triangle star. Any point P of C_2 may be taken as the center of a triangle star of \bar{C}_2 . For if P is on a 1-cell a_i^1 of C_2 it can be chosen as the corre-

sponding P_i^1 and if it is on a 2-cell α_i^2 it can be chosen as the corresponding P_i^2 . The set of all triangle stars of a given regular complex is such that each point of the complex is in at least one of them.

If C_2 is itself regular any two vertices of C_2 which are within or on the boundary of a triangle star of \bar{C}_2 are joined by a 1-cell of C_2 .

15. The method of regular subdivision is useful in continuity arguments where it is desirable to subdivide a given complex into "arbitrarily small" cells. Let a complex C_2 in which a definition of straight lines and of distance has been introduced as described in § 8, be subjected to a regular subdivision into a complex C_2^1 and let C_2^1 be regularly subdivided into C_2^2 , and so on, thus determining a sequence of complexes $C_2, C_2^1, \dots, C_2^n, \dots$, each of which is a regular subdivision of the one preceding it. Let us require also that each new 0-cell introduced in a 1-cell in the process of subdivision shall be the mid-point of the 1-cell, that each point interior to a triangular 2-cell (the point P_k^2 of § 13) shall be the center of gravity (intersection point of the medians) of the triangle, and that the 1-cells introduced shall be straight. With these conventions, it is evident that for every number $\delta > 0$ there exists a number N_δ such that if $n > N_\delta$ every 1-cell in C_2^n is of length less than δ .

16. The relationship between C_2 and C_2 may be stated as follows: (1) each 2-cell α_k^2 of C_2 is composed of P_k^2 and all the 1-cells $P_i^0 P_k^2$ or $P_j^1 P_k^2$ and all 2-cells $P_i^0 P_j^1 P_k^2$, of \bar{C}_2 incident with P_k^2 ; (2) each 1-cell α_j^1 of C_2 is composed of P_j^1 and the two 1-cells $P_i^0 P_j^1$ of \bar{C}_2 incident with P_j^1 ; and (3) each 0-cell α_i^0 of C_2 is the vertex P_i^0 of \bar{C}_2 .

Hence the complex \bar{C}_2 may be converted into C_2 by a series of steps of two sorts; (1) combine two 2-cells whose boundaries have one and only one 1-cell in common into a new 2-cell, suppressing the common 1-cell and (2) combine two 1-cells both incident with a 0-cell which is not incident with any other 1-cell into a new 1-cell, suppressing the common 0-cell.

The first type of step requires that the matrix H_2 of \bar{C}_2 be modified by adding the column representing one of the two 2-cells to the one representing the other, removing the column representing the first of the two 2-cells, and also removing the row corresponding to the 1-cell which is suppressed. The row which is removed contained only two 1's before the two columns were added, because the 1-cell to which it corresponds is incident with only two 2-cells. After the one column is added to the other this row contains only one 1 and this 1 is common to the row and column removed. Hence the first type of step has the effect of reducing the rank of H_2 by 1.

It also has the effect of removing the column of H_1 corresponding to the 1-cell suppressed. This 1-cell is on the boundary of a 2-cell. Hence the 0-circuit represented by the column removed is linearly dependent on the columns corresponding to the other 1-cells of the boundary of this 2-cell. Hence the removal of this column leaves the rank of H_1 unaltered.

The first type of step thus changes q_2 and q_1 into $q_2 - 1$ and q_1 respectively. It obviously changes α_0, α_1 , and α_2 into $\alpha_0, \alpha_1 - 1$ and $\alpha_2 - 1$ respectively. A similar argument shows that the second type of step changes q_2 and q_1 into q_2 and $q_1 - 1$ respectively and also changes $\alpha_0, \alpha_1, \alpha_2$ into $\alpha_0 - 1, \alpha_1 - 1$, and α_2 respectively. Hence the numbers

$$\begin{aligned} \alpha_0 - \alpha_1 + \alpha_2 \\ \alpha_1 - q_1 - q_2 \\ \alpha_2 - q_2 \end{aligned}$$

are the same for \bar{C}_2 as for C_2 . This is a special case of the more general theorem, to be proved later, that these numbers are invariants of C_2 under the group of all homeomorphisms.

Manifolds and 2-Circuits

17. By the *boundary* of a 2-dimensional complex C_2 is meant the one-dimensional complex containing each 1-cell of C_2 which is incident with an odd number of 2-cells of C_2 .

By a *2-dimensional circuit* or a *2-circuit* is meant a 2-dimensional complex C_2 without a boundary such that any 2-dimensional complex whose 2-cells are a subset of the 2-cells of C_2 has a boundary. Thus any 2-dimensional complex in which each 1-cell is incident with an even number of 2-cells is evidently a 2-circuit or a set of 2-circuits having only 0-cells and 1-cells in common.

A 2-dimensional complex containing no 2-circuits is called a 2-dimensional *tree*.

18. By a *neighborhood* of a point P of a complex C_2 is meant any set S of 0-cells, 1-cells and 2-cells composed of points of C_2 and such that any set of points of C_2 having P as a limit point contains points on the cells of S . Thus any triangle star of a regular complex is a neighborhood of its center. Since (cf. § 14) any point of a complex C_2 can be made a vertex of a regular subdivision of C_2 , the process of regular subdivision gives an explicit method of finding a neighborhood of any point of C_2 .

19. If C_2 is a 2-circuit of which every point has a neighborhood which is a 2-cell, then the set of all points on C_2 is called a *closed two-dimensional manifold*.* If C_2 is a regular subdivision of a 2-circuit C_2 then it is evident that C_2 defines a manifold if and only if it is true that for each vertex P of C_2 the incidence relations between the 1-cells and 2-cells of C_2 which are incident with P are the same as those between the 0-cells and 1-cells of a 1-circuit.

A set of points obtainable from a closed two-dimensional manifold by removing a finite number of 2-cells no two of which have an interior or boundary point in common is called an *open two-dimensional manifold*. In the rest of this chapter the term manifold will mean "closed manifold" unless the opposite is specified.

20. The simplest example of a two-dimensional manifold

* We use this term rather than "surface" in order to have a terminology which may be used without confusion in Algebraic Geometry. In the latter science the real and complex points of a surface constitute a four-dimensional manifold.

is one determined by a complex consisting of two 0-cells, two 1-cells and two 2-cells, each 0-cell being incident with both 1-cells and each 1-cell with both 2-cells. Thus the matrices defining the manifold are

$$H_0 = \parallel 1 \quad 1 \parallel, \quad H_1 = H_2 = \begin{vmatrix} 1 & 1 \\ 1 & 1 \end{vmatrix}.$$

Such a manifold is called a *two-dimensional sphere*. It is easily seen to be homeomorphic with the surface of a tetrahedron.

21. A simple example of an open manifold, M_2 , is obtained from a rectangle $ABCD$ (Fig. 4) by setting up a 1-1 continuous correspondence F between the 1-cells AB and CD and their ends in such a way that A corresponds to D and B corresponds to C , and then regarding the pairs of points

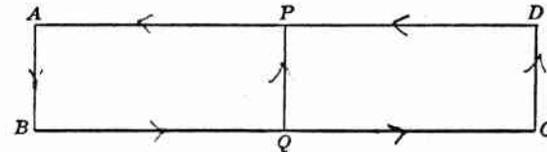


FIG. 4.

which correspond under F each as a single point of M_2 . This open manifold is called a *tube* or a *cylindrical surface*. That it satisfies the definition of an open manifold is easily proved by dividing the rectangle into 2-cells by a 1-cell joining a point P of the side AD to a point Q of the side BC . It is bounded by the two curves formed from the 1-cells AD and BC respectively.

Let a (1-1) continuous correspondence F^1 be set up between the 1-cells AD and BC and their ends in such a way that A corresponds to B , P to Q , and D to C . A closed manifold T is defined by regarding as single points of T each pair of points which correspond either under F or under F^1 . The four points A, B, C, D thus coalesce to one point of T . This manifold is called an *anchor ring* or *torus*.

22. If a correspondence G between the 1-cells AB and CD and their ends is set up in such a way that A corresponds to C

and B to D , an open manifold M is obtained by regarding each pair of points which correspond under G as a single point of M . This open manifold is called the *Möbius band*.^{*} A model is most simply constructed by taking a rectangle, giving it a half-twist and bringing opposite edges together. Thus the rectangle in Fig. 4 represents a Möbius band (Fig. 5) if we regard as identical

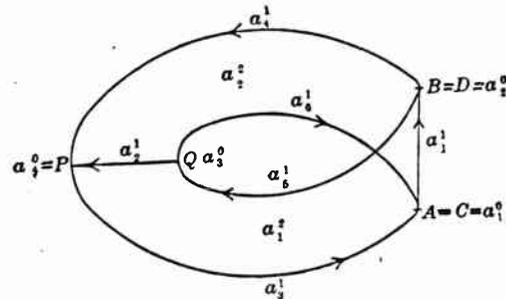


FIG. 5.

the two vertices labelled a_1^0 , the two edges labelled a_1^1 and the two vertices a_2^0 . If the rectangle be divided into two 2-cells by the 1-cell a_2^1 joining the two points a_3^0 and a_4^0 we obtain the following matrices which describe the Möbius band.

$$H_0 = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix},$$

$$H_1 = \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 1 & 0 & 0 \end{pmatrix}, \quad H_2 = \begin{pmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

23. The Möbius band is bounded by the 1-circuit $(0, 0, 1, 1, 1, 1)$. If a 2-cell be introduced which is bounded by this 1-circuit a complex is obtained whose matrices H_0 and H_1 are the same as H_0 and H_1 for the Möbius band, while

^{*} Cf. A. F. Möbius, *Gesammelte Werke*, Vol. 2, pages 484 and 519.

$$H_2 = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{pmatrix}.$$

The set of points on this complex is a manifold homeomorphic with the projective plane. Another set of matrices for the projective plane and some discussion of its Analysis Situs properties will be found in Veblen and Young's *Projective Geometry*, Vol. II, Chap. IX.

24. The operation of adding two one-dimensional complexes, modulo 2, which was defined in § 15, Chap. I may be extended to two dimensions as follows. Let C_2 and C_2^1 be two 2-dimensional complexes each of which is a sub-complex of a given complex C_2^2 . By

$$C_2 + C_2^1 \pmod{2}$$

is meant the complex composed of those 2-cells and their boundaries which are in either of C_2 and C_2^1 but not in both. This operation has the obvious property that if C_2 and C_2^1 are 2-circuits $C_2 + C_2^1 \pmod{2}$ is also a 2-circuit or set of 2-circuits.

25. Let a sphere, S , be decomposed into cells by the process described in § 11 and let $s_1^2, s_2^2, \dots, s_p^2$ be p of the 2-cells so obtained. Let T^1, T^2, \dots, T^p be p anchor rings no two of which have a point in common and which are such that s_i^2 ($i = 1, 2, \dots, p$) is a 2-cell of T^i while T^i and S have no other points in common than those of s_i^2 and its boundary. The set of all points on the 2-circuit,

$$(1) \quad M_2 = S + T^1 + T^2 + \dots + T^p \pmod{2},$$

is called a *sphere with p handles*, or an *orientable manifold of genus p* , or an *orientable manifold of connectivity $2p + 1$* . The proof that the set of points on M_2 is a manifold is made by subdividing it into 2-cells. By the same device it

is easy to prove that a sphere with one handle is an anchor ring.

26. If one of the anchor rings T^i in the last section is replaced by a projective plane, the 2-circuit M_2 is easily seen to define a manifold. We shall refer to this as a *one-sided manifold of the first kind of genus $p-1$, or of connectivity $2p$* . It is easy to verify that a projective plane is a one-sided manifold of the first kind of genus zero.

If two of the manifolds T^i are projective planes and the rest are anchor rings the 2-circuit M_2 again defines a manifold. This is called a *one-sided manifold of the second kind of genus $p-2$, or of connectivity $2p-1$* .

In this section and the last one the terms connectivity and genus are used in such a way that

$$R_1 - 1 = 2p + k$$

where R_1 is the connectivity, p is the genus, and $k = 0$ for an orientable manifold, $k = 1$ for an one-sided manifold of the first kind, and $k = 2$ for an one-sided manifold of the second kind.

27. The fundamental problem of two-dimensional Analysis Situs is that of classifying all two-dimensional manifolds. The solution of this problem is found by proving: (1) that for every manifold there is an integer R_1 , the connectivity (cf. § 29), which is an invariant under the group of all homeomorphisms; (2) that there is an invariant property, that of "orientableness"; and (3) that any two manifolds which have the same connectivity and are both orientable or both non-orientable are homeomorphic. From this it will follow that the examples given in §§ 25 and 26 include all two-dimensional manifolds.

The proof of the propositions (1) and (2) will be given in considerable detail in the following pages because it is the basis of important generalizations to n -dimensions. The third proposition is covered more summarily because methods of proving it are well known and there is no possibility of generalizing it directly to n -dimensions. There is no known

system of invariants or invariant properties of n -dimensional manifolds which will characterize a manifold completely even in the three-dimensional case.

The Connectivity R_1

28. The boundary of any of the 2-cells α_i^2 which enter into the definition of a complex C_2 is given by one of the columns of the matrix H_2 . The boundary of the complex determined by two of these 2-cells is evidently the sum (mod. 2) of the boundaries of the 2-cells, and therefore is a 1-circuit or set of 1-circuits composed of cells α_i^0 and α_j^1 of C_2 . By a repetition of these considerations it follows that the boundary of any two-dimensional complex composed of cells of C_2 is a 1-circuit or set of 1-circuits which is the sum (mod. 2) of the boundaries of the 2-cells of the complex. Hence a symbol $(x_1, x_2, \dots, x_{\alpha_1})$ for such a boundary is linearly dependent (mod. 2) on the columns of H_2 .

Moreover if any symbol $(x_1, x_2, \dots, x_{\alpha_1})$ is linearly expressible in terms of the columns of H_2 this expression determines a set of 2-cells of C_2 such that the symbol for the sum of their boundaries is $(x_1, x_2, \dots, x_{\alpha_1})$. Hence a *necessary and sufficient condition that a set of 1-circuits composed of cells of C_2 shall bound a complex composed of cells of C_2 is that its symbol shall be linearly dependent on the columns of H_2* .

29. By § 25, Chap. I the number of solutions of the equations (H_1) in a complete set is $\alpha_1 - \rho_1$. So this is the number of 1-circuits in a complete set. If ρ_2 is the rank of H_2 , the 1-circuits which bound complexes composed of cells of C_2 are all linearly dependent on ρ_2 such 1-circuits. Hence a complete set of solutions of (H_1) is obtained by adjoining the symbols for $\alpha_1 - \rho_1 - \rho_2$ 1-circuits or sets of 1-circuits to ρ_2 linearly independent columns of H_2 . Let us set

$$(1) \quad R_1 - 1 = \alpha_1 - \rho_1 - \rho_2.$$

Hence there exist $R_1 - 1$ 1-circuits or sets of 1-circuits $C_1^1, C_1^2, \dots, C_1^{R_1-1}$ such that every 1-circuit composed of

1-cells of C_2 is linearly dependent (mod. 2) on these and on the boundaries of 2-cells of C_2 .

It can be so arranged that each of $C_1^1, C_1^2, \dots, C_1^{R_1-1}$ is a single 1-circuit. For if C_1^1 represents more than one 1-circuit it is the sum (mod. 2) of these 1-circuits and at least one of these must be linearly independent of $C_1^2, \dots, C_1^{R_1-1}$ and the bounding circuits, for otherwise C_1^1 would itself be linearly dependent on them. Let C_1^1 be replaced by this non-bounding 1-circuit. In like manner, there is at least one one among the 1-circuits represented by C_1^2 which is linearly independent of $C_1^1, C_1^3, \dots, C_1^{R_1-1}$ and the bounding 1-circuits, for otherwise C_1^2 would be linearly dependent on them. Let C_1^2 be replaced by this 1-circuit and let a similar treatment be applied to C_1^3 , and so on. A set of 1-circuits thus determined is called a *complete set of non-bounding 1-circuits*. It has the properties: (1) There is no two-dimensional complex composed of cells of C_2 which is bounded by these 1-circuits or any subset of them. (2) If C_1 is any 1-circuit composed of cells of C_2 there is a two-dimensional complex composed of cells of C_2 which is bounded either by C_1 alone or by C_1 and some of the circuits C_1^i ($i = 1, 2, \dots, R_1 - 1$). The number, R_1 , is called the *connectivity* of the complex C_2 , or, when it is necessary to distinguish it from the other connectivities R_i which are defined later, the *linear connectivity*.

30. Now suppose that C_2 consists of a single 2-circuit. In this case the sum (modulo 2) of the 1-circuits bounding the 2-cells is $(0, 0, \dots, 0)$. This constitutes one linear relation among the columns of H_2 . There cannot be more than one such relation, for this would imply that a subset of the 2-cells satisfied the definition of a 2-circuit. Hence the rank of H_2 is $\alpha_2 - 1$. Thus we have

$$(2) \quad q_2 = \alpha_2 - 1,$$

and from § 20, Chap. I we have

$$(3) \quad q_1 = \alpha_0 - R_0.$$

But since any 2-circuit is connected, $R_0 = 1$. Hence on combining (2) and (3) with (1) of § 29 we obtain

$$(4) \quad \alpha_0 - \alpha_1 + \alpha_2 = 3 - R_1.$$

This is one of the generalizations of Euler's well-known formula for a polyhedron.

31. Since a two-dimensional closed manifold is the set of points on a particular kind of 2-circuit the formula (4) of § 30, gives the relation between the connectivity R_1 and the characteristic of any two-dimensional complex defining a closed manifold. In the case of an open manifold, M_2 , according to § 19, the boundary consists of a number of curves. Call this number B_1 . Of these curves, $B_1 - 1$ are linearly independent because otherwise they would be the boundary of a manifold contained in M_2 , contrary to definition. As in § 29, a complete set of 1-circuits in the complex C_2 defining M_2 may be taken to consist of q_2 bounding 1-circuits and $R_1 - 1$ non-bounding 1-circuits; and of the latter, $B_1 - 1$ may be taken to be circuits of the boundary of M_2 . Hence if $R_1 - B_1 = \bar{R}_1 - 1$, the non-bounding circuits in the complete set comprise $B_1 - 1$ from the boundary and $R_1 - 1$ others.

If C_2 be modified by introducing B_1 2-cells each bounded by one of the B_1 1-circuits of the boundary, C_2 becomes a 2-circuit C_2^1 of $\alpha_2 + B_1$ 2-cells, α_1 1-cells, and α_0 0-cells in which $B_1 - 1$ of the non-bounding circuits of C_2 have become bounding circuits. Hence C_2^1 has the connectivity \bar{R}_1 . Hence

$$\alpha_0 - \alpha_1 + \alpha_2 + B_1 = 3 - \bar{R}_1,$$

and

$$\begin{aligned} \alpha_0 - \alpha_1 + \alpha_2 &= 3 - \bar{R}_1 - B_1 \\ &= 2 - R_1 \end{aligned}$$

which is the formula for the characteristic of a complex defining an open manifold of two dimensions. The same formula holds for any connected two-dimensional tree, as follows from (1) and (3) and the fact that $q_2 = \alpha_2$.

Singular Complexes

32. The cells a_i^0, a_j^1, a_k^2 which enter into the definition of a complex are all non-singular and their boundaries are also non-singular. This restriction was necessary in order to obtain the theorem of § 6 that the matrices H_0, H_1, H_2 fully determine the complex. In many applications, however, it is desirable to drop the restriction that the boundaries of the cells referred to in the matrices H_i shall be non-singular. The results of the theory of matrices can in general be applied whenever it is possible to subdivide the cells having singular boundaries by means of a finite number of 0-cells and 1-cells in such a way as to obtain a complex of non-singular cells with non-singular boundaries.

For example, in § 21 the anchor ring was defined as consisting of one 0-cell, represented by the four vertices of the rectangle, two 1-cells represented by its pairs of opposite edges, and one 2-cell. The matrices of incidence relations of these cells are

$$H_0 = \parallel 1 \parallel, \quad H_1 = \parallel 0 \ 0 \parallel, \quad H_2 = \begin{vmatrix} 0 \\ 0 \end{vmatrix}.$$

Thus $e_0 = 1, e_1 = 0, e_2 = 0, \alpha_0 = 1, \alpha_1 = 2, \alpha_2 = 1$. Hence

$$R_1 = 3 - (\alpha_0 - \alpha_1 + \alpha_2) = 3 \\ = \alpha_1 - e_1 - e_2 + 1.$$

If the rectangle is subdivided into triangles so that a non-singular complex is obtained it will be found that the same value for R_1 will be obtained from the non-singular complex as from the singular one.

33. The notion of a singular complex on a one-dimensional complex, as defined in § 8, Chap. I, can be generalized directly to two dimensions as follows:

Let C_2 be a two-dimensional complex, C' a generalized complex of zero, one or two dimensions*, and F a correspondence

* The definition may be extended so that C' is of any number of dimensions.

in which each point of C' corresponds to one point of a set of points $[P]$ of C_2 while each P is the correspondent of one or more points of C' . If C' is of one or two dimensions we require F to be continuous. Under these conditions, any point X of C' associated with the P to which it corresponds under F is called a point on C_2 ; it is referred as the image of X under F and is uniquely denoted by $F(X)$; it is said to coincide with P and P is said to coincide with it. The point $F(X_1)$ is called a limit point of the points $F(X)$ if X_1 is a limit point of the points X . The set of all points $F(X)$ on C_2 is in a (1-1) continuous correspondence with the points of C' and thus constitutes a complex C'' identical in structure with C' . The complex C'' is said to be on C_2 . If any of the points P is the correspondent under F of more than one point of C' , C'' is called a singular complex on C_2 and the point P in question is called a singular point. If F is (1-1), C'' is said to be non-singular. A cell of C'' is said to coincide with a cell of C_2 if and only if the two cells are in (1-1) continuous correspondence, under F .

In case C'' is two-dimensional and such that there is at least one point of C'' on each point of C_2 and if, furthermore, there exists for every point of C'' a neighborhood which is a non-singular complex on C_2 , then C'' is said to cover C_2 . In case the number of points of C'' on each point of C_2 is finite and equal to n , C'' is said to cover C_2 n times (cf. § 9, Chap. I).

34. Any 2-circuit which is not a manifold can be regarded as a singular manifold. For let C_2 be an arbitrary 2-circuit. Each of its edges, a_i^1 , is incident with an even number, $2n_i$, of 2-cells. These 2-cells may be grouped arbitrarily in n_i pairs no two of which have a 2-cell in common; let these be called the pairs of 2-cells associated with a_i^1 . Let C_2' be a 2-circuit on C_2 such that (1) there is one and but one 2-cell of C_2' coinciding with each 2-cell of C_2 , (2) there are n_i 1-cells of C_2' coinciding with each 1-cell a_i^1 of C_2 , each of the n_i 1-cells being incident with a pair of 2-cells of C_2' which coincide with one of the pairs of 2-cells associated

with a_i^1 , and (3) there is one 0-cell of C_2' coincident with each 0-cell a_i^0 of C_2 , this 0-cell being incident with all the 1-cells of C_2' which coincide with 1-cells of C_2 incident with a_i^0 . Thus C_2' has two 2-cells incident with each of its 1-cells.

The incidence relations of the 1-cells and 2-cells of C_2' which are incident with a vertex a_i^0 of C_2' are the same as those of the 0-cells and 1-cells of a linear graph and since there are just two 2-cells incident with each 1-cell this linear graph consists of a number of 1-circuits having no points in common. Let any set of 1-cells and 2-cells of C_2' which are incident with a_i^0 and whose incidence relations with one another are those of a 1-circuit be called a *group associated with a_i^0* . Let C_2'' be a 2-circuit on C_2' such that (1) there is one and but one i -cell ($i = 1, 2$) of C_2'' coinciding with each i -cell of C_2' , (2) the incidence relations between the 1-cells and 2-cells of C_2'' are the same as those between the cells of C_2' with which they coincide, and (3) there is one 0-cell of C_2'' for each group associated with each vertex a_i^0 of C_2' and this 0-cell is coincident with a_i^0 and incident with those and only those 1-cells and 2-cells of C_2'' which coincide with 1-cells and 2-cells of the group. The set of points on the complex C_2'' is a two-dimensional manifold, by § 19, and C_2'' is a singular complex on C_2 . Hence C_2 may be obtained by coalescing a certain number of 1-cells and 0-cells of a manifold.

Bounding and Non-bounding 1-Circuits

35. Having defined what is meant by saying that a complex C_n ($n = 0, 1, 2$) is on a complex C_2 , we can now state and solve the problem of bounding and non-bounding circuits in a perfectly general form: *Given any set of 1-circuits K_1 on a complex C_2 , does there exist a two-dimensional complex K_2 on C_2 which is bounded by K_1 ?*

In spite of the generality of the complex K_1 , and because of the generality of K_2 , this problem is free from many of the difficulties inherent in such point-set theorems as those

of Schoenflies and Jordan. This will be illustrated by the simple case considered in the next section.

36. Any closed curve, singular or not, which is on a 2-cell a^2 and its boundary but does not pass through every point of a^2 is the boundary of a 2-cell on a^2 . Let c be the given curve and O a point of a^2 not on c . Let OX be the straight 1-cell joining O to a variable point X of c . Let O' be a point interior to a triangle t of a Euclidean plane and let X' be a variable point of the boundary of this triangle. Let F be a continuous (1-1) correspondence between the set of points $[X']$ and the set of points $[X]$. If we let each point of $O'X'$ correspond to the point of OX which divides it in the same ratio, a continuous correspondence F' is defined in which each point of the interior and boundary of the triangle t corresponds to one point of a^2 . By § 1 there is thus defined a 2-cell (in general, singular) which is bounded by c .

It is not essential that O shall not coincide with a point of c , for in case X coincides with O the interval OX may be taken to be a singular one coinciding with O . Hence we have without restrictions the theorem that any closed curve on a 2-cell a is the boundary of a 2-cell on a .

The theorem may be generalized slightly as follows: *Any curve c on a triangle star and its boundary (§ 14) is the boundary of a 2-cell on the triangle star. The 2-cell is constructed as above, taking the center of the triangle star as O .*

Congruences and Homologies, Modulo 2

37. Before going on to the solution of the problem stated in § 35, let us introduce a notation which is adapted from that of Poincaré. We shall say that a complex C_n ($n = 1, 2$) is *congruent (mod. 2)* to a set of $(n-1)$ -circuits C_{n-1} if and only if C_{n-1} is the boundary of C_n . This is represented by the notation

$$(1) \quad C_n \equiv C_{n-1} \pmod{2}.$$

In case C_{n-1} fails to exist, so that C_n is a set of n -circuits, C_n is said to be *congruent to zero (mod. 2)* and (1) is replaced by

$$(2) \quad C_n \equiv 0 \pmod{2}.$$

Expressions of the form (1) and (2) are called *congruences (mod. 2)*. They have been defined thus far only for $n = 1$ and $n = 2$, but these definitions will apply for all values of n as soon as the terms complex, n -circuit, and boundary of an n -dimensional complex have been defined for all values of n .

Both in the one- and two-dimensional cases it is evident that when two complexes are added (mod. 2) the boundary of the sum is the sum (mod. 2) of the boundaries. Hence the sum (mod. 2) of the left-hand members of two congruences is congruent to the sum (mod. 2) of the right-hand members. Or, more generally, *any linear combination (mod. 2) of a number of valid congruences (mod. 2) of the same dimensionality is a valid congruence (mod. 2)*.

38. With respect to a complex C a complex C_{n-1} is said to be *homologous to zero (mod. 2)* if and only if it is the right-hand member of a congruence such as (1) in which C_n represents a complex on C . This relation is indicated by

$$(3) \quad C_{n-1} \sim 0 \pmod{2}.$$

Thus

$$C_0 \sim 0 \pmod{2}$$

means that C_0 represents a set of 0-circuits which bound a one-dimensional complex on C , and

$$C_1 \sim 0 \pmod{2}$$

means that C_1 represents a set of 1-circuits on C which bound a two-dimensional complex on C . Thus in every case, (3) implies

$$(4) \quad C_{n-1} \equiv 0 \pmod{2},$$

but (4) does not imply (3).

From the corresponding proposition in the last section it follows at once that *any linear combination (mod. 2) of a set of valid homologies (mod. 2) is a valid homology (mod. 2)*.

A homology,

$$(5) \quad C_{n-1} + C'_{n-1} \sim 0 \pmod{2},$$

is also written

$$(6) \quad C_{n-1} \sim C'_{n-1} \pmod{2}.$$

The homology (6) evidently means that there exists a complex C_n on C which is bounded by C_{n-1} and C'_{n-1} .

If \bar{C}_1 is a 1-circuit obtained by introducing new vertices in a 1-circuit C_1 , it is evident that

$$C_1 \sim \bar{C}_1 \pmod{2},$$

because C_1 and \bar{C}_1 bound a singular two-dimensional complex coincident with them both.

The Correspondence A

39. The first step toward the solution of the problem of § 35 will be to show that if \bar{C}_2 is a regular subdivision of C_2 , then for any 1-circuit K_1 on C_2 there is a set of 1-circuits K'_1 composed of cells of C_2 such that

$$(1) \quad K_1 \sim K'_1 \pmod{2}.$$

This has the consequence that any homology among 1-circuits can be replaced by one in which each 1-circuit is composed of cells of C_2 ; and the problem of § 35 is reduced to that of finding a necessary and sufficient condition that $K'_1 \sim 0 \pmod{2}$ if K'_1 represents a set of 1-circuits composed of cells of C_2 . The next three sections aim at establishing the homology (1).

40. Let K be a one- or two-dimensional complex on a two-dimensional complex C_2 . Let C_2 be a regular subdivision of C_2 . Let a definition of distance and straightness be introduced relative to C_2 , and let \bar{C}_2 be a regular subdivision of C_2 whose 1-cells are all straight. The triangle stars of \bar{C}_2 constitute a set of overlapping neighborhoods such that every point of \bar{C}_2 is interior to at least one of these neighborhoods. Hence by simple continuity considerations (Heine-Borel theorem) K can be subdivided, by introducing new vertices if it is of one dimension, or by the process of regular subdivision (§ 13) if it is of two dimensions into a complex \bar{K} such that for each 1-cell or 2-cell of K there is a triangle star of \bar{C}_2 to which it is interior.

Those of the triangle stars of \bar{C}_2 whose centers are vertices of \bar{C}_2 have the property that any point of \bar{C}_2 is either interior to one such triangle star or on the boundaries of 2-cells from two or more such triangle stars. Let us designate as a correspondence A any correspondence of the vertices of \bar{K} with those of \bar{C}_2 by which each vertex of \bar{K} which is interior to a triangle star of \bar{C}_2 having a vertex of \bar{C}_2 as center corresponds to this center, and each vertex of \bar{K} which is on the boundary of two or more such triangle stars corresponds to the center of one of them.* Thus a correspondence A determines a unique vertex of C_2 for each vertex of K .

This construction is such that any triangle star of \bar{C}_2 which contains a vertex of K has the 0-cell of C_2 to which this vertex corresponds on its interior or boundary. Moreover any two vertices of K which are ends of the same 1-cell of \bar{K} coincide with points of the same triangle star of \bar{C}_2 and hence correspond to points of C_2 of the interior or boundary of this triangle star. Hence they correspond either to the same vertex of C_2 or to the two ends of a 1-cell of C_2 (Cf. § 14). In case K is two-dimensional it follows similarly that any three vertices of \bar{K} incident with the same 2-cell of K correspond to one or more vertices of a single 2-cell of C_2 .

41. Let the 0-cells, 1-cells and 2-cells of \bar{C}_2 be denoted by $c_1^0, c_2^0, \dots, c_{\alpha_0}^0; c_1^1, c_2^1, \dots, c_{\alpha_1}^1; \text{ and } c_1^2, c_2^2, \dots, c_{\alpha_2}^2$ respectively; and those of \bar{K} by $k_1^0, k_2^0, \dots, k_{\beta_0}^0; k_1^1, k_2^1, \dots, k_{\beta_1}^1; k_1^2, k_2^2, \dots, k_{\beta_2}^2$ respectively. Having fixed on a correspondence A between the vertices of K and those of C_2 , let each 0-cell k_i^0 be joined by a straight 1-cell b_i^1 to the corresponding vertex of \bar{C}_2 in case k_i^0 does not coincide with its correspondent; and if k_i^0 does coincide with its correspondent let it be joined to its correspondent by a singular 1-cell b_i^1 coinciding with it.

The two ends of a 1-cell k_i^1 are thus joined by two 1-cells b_i^1 and b_k^1 either to the same vertex of C_2 or to the two ends

* This is essentially the same as requiring (with Alexander, in the paper cited in our preface) that each vertex of K shall correspond to the nearest vertex of \bar{C}_2 , or to one of the nearest if there are more than one.

of a 1-cell c_p^1 of \bar{C}_2 . In the first case k_i^1, b_j^1 and b_k^1 are the 1-cells of a 1-circuit and in the second case k_i^1, b_j^1, b_k^1 and c_p^1 are the 1-cells of a 1-circuit. In either case there is a single triangle star of \bar{C}_2 which, with its boundary, contains the 1-circuit. Therefore by § 36 the 1-circuit bounds a 2-cell b_i^2 on \bar{C}_2 . Thus each 1-cell k_i^1 of \bar{K} determines a 2-cell b_i^2 . The complex composed of the 2-cells b_i^2 and their boundaries is called B_2 .

42. The incidence relations between the 1-cells b_j^1 and the 2-cells b_i^2 of B_2 are the same as the incidence relations between the 0-cells and 1-cells of \bar{K} . Hence, in particular, if \bar{K} is a 1-circuit or set of 1-circuits, K_1 , the sum (mod. 2) of the boundaries of the 2-cells b_i^2 contains none of the 1-cells b_j^1 . Hence the boundary of B_2 can consist only of cells of K_1 and of \bar{C}_2 . Hence the boundary of B_2 is either K_1 alone or K_1 and a set of 1-circuits composed of cells of \bar{C}_2 . Let the latter set of 1-circuits be denoted by K'_1 .

Hence we have the congruence,

$$(2) \quad B_2 \equiv K_1 + K'_1 \pmod{2}$$

in which K'_1 is either zero or a set of 1-circuits composed of cells of C_2 . From this there follows the homology

$$(1) \quad K_1 \sim K'_1 \pmod{2}$$

which we have been seeking.

43. If K'_1 is zero the question as to whether K_1 satisfies a homology

$$(3) \quad K_1 \sim 0 \pmod{2}$$

is answered in the affirmative. In any other case, since K'_1 is composed of cells of \bar{C}_2 it is represented by a symbol $(x_1, x_2, \dots, x_{\alpha_1})$. If this symbol is linearly dependent on the columns of the matrix H_2 for \bar{C}_2 ,

$$K'_1 \sim 0 \pmod{2}$$

according to § 28. Moreover K'_1 cannot bound a complex composed of cells of \bar{C}_2 unless its symbol $(x_1, x_2, \dots, x_{\alpha_1})$ is

linearly dependent on the columns of H_2 . If, therefore, we can prove that K'_1 cannot bound any complex on C_2 , unless it bounds one composed of cells of \bar{C}_2 , it will follow that (3) is satisfied if and only if $(x_1, x_2, \dots, x_{\alpha_1})$ is linearly dependent on the columns of H_2 . This we proceed to do, thus completing the solution of the problem stated in § 35.

44. Let us return to the notations of §§ 40 and 41 and suppose that K is a two-dimensional complex K_2 . The three 1-cells k_i^1, k_j^1, k_l^1 of K_2 incident with a 2-cell k_p^2 of \bar{K}_2 have been seen to determine three 2-cells b_i^2, b_j^2, b_l^2 . These 2-cells are incident by pairs with the 1-cells joining the three vertices of k_p^2 to their correspondents under the correspondence A . The vertices of C_2 to which the vertices of k_p^2 correspond are either the three vertices of a 2-cell c_q^2 of C_2 or the two ends of a 1-cell of C_2 or a single 0-cell of C_2 . In the first case the 2-cells, $k_p^2, b_i^2, b_j^2, b_l^2$ and c_q^2 are the 2-cells of a sphere; in the second and third cases the 2-cells k_p^2, b_i^2, b_j^2 , and b_l^2 are the 2-cells of a sphere. Let the sphere which is thus in every case determined by k_p^2 be denoted by S_p^2 .

A 2-cell b_i^2 is in an odd number of these spheres if and only if it is incident with a 1-cell k_i^1 of the boundary of K_2 . Hence the result of adding the spheres S_p^2 to $K_2 \pmod{2}$ is either zero or a complex K'_2 the 2-cells of which are either 2-cells of \bar{C}_2 or 2-cells b_i^2 determined by the 1-cells of the boundary of \bar{K}_2 . In particular, if \bar{K}_2 is a 2-circuit, either K_2 is the sum $\pmod{2}$ of the spheres S_p^2 or K'_2 is composed entirely of cells of \bar{C}_2 .

45. If K_2 has a boundary, so that

$$(4) \quad K_2 \equiv K_1 \pmod{2},$$

the result of the last section is that by adding a number of congruences,

$$(5) \quad S_p^2 \equiv 0 \pmod{2},$$

to (4) we obtain a congruence,

$$(6) \quad K'_2 \equiv K_1 \pmod{2},$$

such that all 2-cells of K'_2 are either 2-cells of \bar{C}_2 or 2-cells b_i^2 determined by the boundary K_1 of K_2 . The complex B'_2 composed of the latter 2-cells and their boundaries is such that

$$(7) \quad B'_2 \equiv K_1 + K'_1 \pmod{2}$$

where K'_1 is composed of 0-cells and 1-cells of C_2 . On adding (6) and (7) we obtain a congruence

$$(8) \quad K'_2 + B'_2 \equiv K'_1 \pmod{2}$$

in which the left-hand member represents a complex composed only of cells of C_2 .

46. It is now easy to obtain the result required at the end of § 43, namely that if a set of 1-circuits K'_1 is composed of cells of C_2 , then

$$K'_1 \sim 0 \pmod{2}$$

implies that K'_1 is the boundary of a complex composed of cells of \bar{C}_2 . Taking a complex bounded by K'_1 , we subdivide it as above, preliminary to setting up a correspondence A , and denote by K_1 the corresponding subdivision of K'_1 . Thus we have a congruence like (4) of the last section, consequently one like (8) derived from it. But in this case the K'_1 constructed in the last section is easily seen to be identical with K'_1 . Hence (8) states that K'_1 is the boundary of a complex composed of cells of \bar{C}_2 .

Invariance of R_1

47. An immediate corollary of what has just been proved is that the 1-circuits $C_1^1, C_1^2, \dots, C_1^{R_1-1}$ of a complete set (§ 29) of non-bounding 1-circuits of \bar{C}_2 are not connected by any homology of the form

$$(1) \quad C_1^i + C_1^{i_1} + \dots + C_1^{i_k} \sim 0 \pmod{2}$$

in which the superscripts are distinct integers less than R_1 . Moreover if K_1 is any 1-circuit on C_2 it satisfies a homology of the form

$$(2) \quad K_1 \sim C_1^{j_1} + C_1^{j_2} + \dots + C_1^{j_r} \pmod{2}$$

in which the terms of the right-hand member represent 1-circuits of the complete set. For by § 42

$$(3) \quad K_1 \sim K'_1 \pmod{2}$$

in which K'_1 is zero or a set of 1-circuits composed of cells of \bar{C}_2 , and by § 29 K'_1 is homologous to a combination of 1-circuits of the complete set.

48. But if $K_1^1, K_1^2, \dots, K_1^N$ is any set of 1-circuits such that (1) any 1-circuit is homologous to a linear combination of them and (2) there is no homology relating them, it is easily proved that $N = R_1 - 1$. For by the properties of the 1-circuits $C_1^1, C_1^2, \dots, C_1^{R_1-1}$, there are N homologies like (2),

$$(4) \quad K_1^j \sim C_1^{j_1} + C_1^{j_2} + \dots + C_1^{j_p} \pmod{2},$$

one for each value of j from 1 to N . If $N > R_1 - 1$ the right-hand members of (4) must satisfy a homology because there are only $R_1 - 1$ C_1^i 's. But this is contrary to the property (2) of the K_1^i 's. Hence $N > R_1 - 1$ is impossible. In like manner, inverting the roles of the K_1^i 's and the C_1^i 's, it follows that $R_1 - 1 > N$ is impossible. Hence $N = R_1 - 1$.

Any homeomorphism of C_2 obviously transforms a set of 1-circuits $K_1^1, K_1^2, \dots, K_1^N$ satisfying the conditions (1) and (2) into a set of 1-circuits satisfying the same conditions. Since $N = R_1 - 1$ for every such set of 1-circuits, it follows that R_1 is an *Analysis Situs* invariant of the complex C_2 .

49. It was proved in § 16 that the expression in the right-hand member of

$$R_1 - 1 = \alpha_1 - \varrho_1 - \varrho_2$$

is the same for C_2 as for \bar{C}_2 . Now let C_2 be subdivided into any set of cells which form a non-singular complex K_2 on C_2 , and let \bar{K}_2 be a regular subdivision of K_2 . The complex \bar{K}_2 can replace \bar{C}_2 in the discussion above and hence \bar{K}_2 has the same connectivity, R_1 , as \bar{C}_2 . Hence K_2 and C_2 have the same connectivity. In other words any two complexes have the same connectivity if they are identical as sets of points and the cells of each are non-singular on the other.

It should perhaps be remarked that the relation between K_2 and C_2 may be quite complex in spite of the fact that each cell of K_2 is non-singular on C_2 and *vice versa*. For any 1-cell of K_2 may intersect any number of 1-cells of C_2 in an infinite set of points, and any 2-cell of K_2 may have an infinite set of regions in common with any 2-cell of C_2 .

Invariance of the 2-Circuit

50. If K_2 and C_2 are related as described in the last section, K_2 is a 2-circuit if and only if C_2 is a 2-circuit. Since the relation between C_2 and K_2 is reciprocal this theorem will be established if we prove that if K_2 is a 2-circuit then C_2 is one. Also it is evident that C_2 or K_2 is a 2-circuit if and only if a regular subdivision of it is a 2-circuit. Hence we replace C_2 by its regular subdivision \bar{C}_2 as in § 40 and construct the spheres S_2^p as in § 44. By § 44 the result of adding the spheres S_2^p to $\bar{K}_2 \pmod{2}$ is either zero or a set of 2-circuits composed of cells of \bar{C}_2 . If it were zero the 2-circuit \bar{K}_2 would be the sum $\pmod{2}$ of the spheres S_2^p . But this is impossible, as shown by the following theorem.

51. *There is no set of 2-circuits K_2^i on a 2-circuit C_2 such that (1) for each 2-circuit K_2^i there is a 2-cell of C_2 on which there is no point of K_2^i and (2) the sum $\pmod{2}$ of the 2-circuits K_2^i is C_2 .*

To prove this theorem, we suppose that there is a set of 2-circuits K_2^i having the property (1). We let these 2-circuits take the place of K in § 40, make the regular subdivision of C_2 into \bar{C}_2 and K_2^i into \bar{K}_2^i , construct a correspondence A and obtain a set of spheres S_2^p (which, of course, must not be confused with those in § 50). When the spheres having 2-cells in common with one of the 2-circuits K_2^i are added to this \bar{K}_2^i the result is either zero or a non-singular set of 2-circuits composed of cells of \bar{C}_2 . But since \bar{C}_2 is a 2-circuit the only 2-circuit composed of its cells is \bar{C}_2 itself. Since there is one 2-cell of C_2 which contains no point of K_2^i it follows that the sum of \bar{K}_2^i and the spheres S_2^p determined by its 2-cells is zero.

Obviously if each of two 2-circuits is such that the sum (mod. 2) of it and the spheres S_2^p determined by its 2-cells is zero the same is true of the sum (mod. 2) of the two 2-circuits. Hence the sum of all the 2-circuits \bar{K}_2^i has this property. On the other hand the 2-circuit \bar{C}_2 is such that the sum of it and the spheres S_2^p determined by its 2-cells is \bar{C}_2 itself. Hence the 2-circuits K_2^i do not have the property (2).

52. Letting the 2-circuit \bar{K}_2 and the spheres S_2^p of § 50 take the place of the 2-circuit C_2 and the 2-circuits K_2^i of § 51 it follows from the theorem of § 51 that \bar{K}_2 is not the sum (mod. 2) of the spheres S_2^p . Hence the sum (mod. 2) of \bar{K}_2 and the spheres S_2^p is a set of 2-circuits composed of cells of \bar{C}_2 . We shall prove that these 2-circuits constitute C_2 . If they did not, let them be denoted by C_2' , let c_2^j be one of the 2-cells of \bar{C}_2 which is not on C_2' , and let \bar{K}_2 be regularly subdivided into a complex K_2' which has at least one 2-cell which is interior to c_2^j .

The complex C_2' is composed of non-singular cells on K_2' and hence C_2' and K_2' can replace \bar{K}_2 and C_2 respectively in the construction used in § 50 for the spheres S_2^p . Thus a set of spheres can be found which when added to a regular subdivision of C_2' give a set of 2-circuits C_2'' composed of cells of a regular subdivision of K_2' . It follows from § 51 that C_2'' is not vacuous. Since \bar{K}_2 and its regular subdivisions are 2-circuits, C_2'' must be identical with the regular subdivision of K_2' . This is not possible unless there is a point of C_2' on each 2-cell of K_2' . But this implies that there is a point of C_2' on c_2^j , contrary to the hypothesis that c_2^j is not a cell of C_2' . Hence C_2' coincides with \bar{C}_2 , as we wished to prove.

Now by reversing the whole process we can show that any one of the 2-circuits that compose C_2' will yield a subdivision of the 2-circuit K_2 . Hence there can be only one, and the proof of the theorem of § 50 is complete.

53. It is an obvious corollary of this theorem that the property of a two-dimensional complex, of being a 2-circuit, is an Analysis Situs invariant. For if C_2 and G_2 are two

complexes which are homeomorphic, the homeomorphism defines a non-singular complex K_2 on C_2 such that each cell of K_2 is the image of a cell of G_2 . By definition, K_2 is a 2-circuit if and only if G_2 is a 2-circuit, and by the theorem of § 50 K_2 is a 2-circuit if and only if C_2 is a 2-circuit.

It is an obvious corollary of this result that the property of a complex, that it defines a manifold, is also an Analysis Situs invariant. In other words, any complex into which a manifold can be subdivided, satisfies the conditions laid down in § 19.

Matrices of Orientation

54. Let us now convert the 1-dimensional complex composed of the 0-cells and 1-cells of C_2 into an oriented one-dimensional complex in the fashion described in §§ 33 to 40 of Chap. I. The oriented 0-cells are

$$\sigma_1^0, \sigma_2^0, \dots, \sigma_{\alpha_0}^0,$$

the 1-cells are

$$\sigma_1^1, \sigma_2^1, \dots, \sigma_{\alpha_1}^1,$$

and the relations between them are given by the matrices E_0, E_1 satisfying the relation

$$E_0 \cdot E_1 = 0.$$

Each of the columns of H_2 is the symbol for a 1-circuit which, according to § 35, Chap. 1, determines two oriented 1-circuits. The symbol for either of these oriented 1-circuits may be obtained from the corresponding column of H_2 by changing some of the 1's to -1's. Hence by changing some of the 1's in H_2 to -1's there is determined a matrix

$$E_2 = \|\epsilon_{ij}^2\| \quad (i = 1, 2, \dots, \alpha_1; j = 1, 2, \dots, \alpha_2)$$

each column of which represents an oriented 1-circuit and is therefore a solution of the equations (E_1) , § 42, Chap. 1. Hence

$$E_1 \cdot E_2 = 0.$$

As an example, a matrix E_2 for the tetrahedron in Fig. 1, page 2, is (cf. H_2 in § 4)

$$E_2 = \begin{vmatrix} 0 & -1 & 1 & 0 \\ 1 & 0 & -1 & 0 \\ -1 & 1 & 0 & 0 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \end{vmatrix}.$$

A further example is furnished by the projective plane, for which (cf. §§ 22, 23)

$$E_1 = \begin{vmatrix} -1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 & -1 & 0 \\ 0 & -1 & 0 & 0 & 1 & -1 \\ 0 & 1 & -1 & 1 & 0 & 0 \end{vmatrix}, \quad E_2 = \begin{vmatrix} 1 & 1 & 0 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{vmatrix}.$$

Note that the rank of E_2 for the tetrahedron is 3, or $\alpha_2 - 1$, and for the projective plane is 3, or α_2 .

55. Let us denote the ranks of E_0, E_1, E_2 by r_0, r_1, r_2 respectively. We have seen that

$$\begin{aligned} r_0 &= R_0 = \varrho_0, \\ r_1 &= \varrho_1 \end{aligned}$$

and that in case C_2 is a 2-circuit,

$$\varrho_2 = \alpha_2 - 1.$$

It is impossible that r_2 should be less than $\alpha_2 - 1$ because this would imply a linear relation involving at most $\alpha_2 - 1$ columns, with relatively prime coefficients, and hence on reducing modulo 2, that the same statement was true of the columns of H_2 , contrary to § 30. Hence there remain two possibilities

$$r_2 = \alpha_2 - 1$$

and

$$r_2 = \alpha_2$$

for any C_2 which is a 2-circuit. The examples in the last section show that both possibilities can be realized.

56. A 2-circuit C_2 such that $r_2 = \alpha_2 - 1$ has the property that if the boundaries of its 2-cells are converted into oriented 1-circuits in any way, they will satisfy a linear relation with integral coefficients. For the columns of E_2 represent a set of oriented 1-circuits, one bounding each 2-cell, and since $r_2 = \alpha_2 - 1$ they are subject to one linear relation,

$$(1) \quad b_1 c_1 + b_2 c_2 + \dots + b_{\alpha_2} c_{\alpha_2} = 0$$

in which the c 's represent the columns of E_2 and the b 's are positive or negative integers or zero. If the coefficients are divided by their highest common factor, and then reduced modulo 2, this relation must state that the sum of the columns of H_2 is zero. Hence the relation must involve all columns of E_2 .

In case C_2 has the property that each 1-cell is incident with two and only two 2-cells (for example, if it is a manifold), if an oriented 1-cell σ_i^1 is to cancel out, the two oriented 1-circuits formed from the boundaries of the 2-cells incident with σ_i^1 must appear in (1) with numerically equal coefficients. It follows that the coefficients of (1) are numerically equal and therefore that by removing a common factor (1) can be reduced to a form in which $b_i = \pm 1$.

Hence by multiplying some of the columns by -1 , E_2 can be reduced to a form in which the sum of the columns is zero. The columns of E_2 then represent a set of oriented 1-circuits such that if σ^1 is any oriented 1-cell formed from a 1-cell of C_2 , one of these 1-circuits contains σ^1 and another one contains $-\sigma^1$. Consequently if C_2 has the property that each of its 1-cells is incident with two and only two 2-cells, the boundaries of its 2-cells can be converted into oriented 1-circuits in such a way that their sum is zero.

Orientable Circuits

57. The theorem of the last section is that if $r_2 = \alpha_2 - 1$ for a 2-circuit C_2 , the boundaries of the 2-cells of C_2 can be converted into oriented 1-circuits in such a way that they

satisfy a linear relation. If $r_2 = \alpha_2$, the boundaries of the 2-cells evidently cannot be thus oriented. In the first case C_2 is said to be *two-sided* or *orientable* and in the second case to be *one-sided* or *non-orientable*. A manifold is said to be *orientable* or *non-orientable* according as the complex defining it is or is not orientable. This extension of the term is justified by the theorems of §§ 58-60 below, according to which the complexes defining a given manifold M_2 are all orientable or all non-orientable.

This definition is equivalent to the one given in 1865 by A. F. Möbius, *Über die Bestimmung des Inhaltes eines Polyeders*, Werke, Vol. 2, p. 475; see also p. 519. The term "orientable" was suggested by J. W. Alexander as preferable to "two-sided" because the latter term connotes the separation of a three-dimensional manifold into two parts, the two "sides," by the two-dimensional manifold, whereas the property which we are dealing with is an internal property of the two-dimensional manifold.*

The intuitional significance of orientableness is perhaps best grasped by experiments with the well-known Möbius paper strip described in the article referred to above. These experiments can also be used to verify the theorems on deformation and on the indicatrix in Chap. V.

58. Suppose that a 2-cell a_2^i of a complex C_2 , the cells of which have been oriented in the manner described above, is separated into two 2-cells by a 1-cell a^1 . The two new 2-cells are bounded by two 1-circuits which have a^1 in common. It is easily seen that if σ^1 is either of the oriented 1-cells formed from a^1 , two oriented 1-circuits can be formed from the

* On the relation between orientableness and two-sidedness, see E. Steinitz, *Sitzungsberichte der Berliner Math. Ges.*, Vol. 7 (1908), p. 35; and D. König, *Archiv der Math. u. Phys.*, 3d Ser., Vol. 19 (1912), p. 214. The term orientable (orientierbar) has also been used by H. Tietze in an article in the *Jahresbericht der Deutschen Math. Ver.*, Vol. 29 (1920), p. 95, which came to my attention while these lectures were in proof-sheets. This article contains a general discussion of orientability covering a number of the questions referred to in the beginning of Chap. V below, and also a useful collection of references.

boundaries of the two new 2-cells in such a way that one of them contains σ^1 and the other contains $-\sigma^1$. Hence the sum of these oriented 1-circuits is one of the two oriented 1-circuits which can be formed from the boundary of a_2^i .

The complex C_2 is converted into a new complex C_2' by introducing the new 1-cell a^1 and subdividing a_2^i . The matrix E_2 of C_2' has one row and one column more than the matrix E_2 of C_2 , and by the paragraph above can be converted into the matrix E_2 for C_2 by adding the two columns corresponding to the two new 2-cells and striking out the row corresponding to a^1 . These operations evidently reduce the rank by 1. Hence the rank of E_2 for C_2' is equal to the number of 2-cells of C_2' if and only if the rank of E_2 for C_2 is equal to the number of 2-cells of C_2 .

Since a regular subdivision of C_2 can be effected by the two operations of introducing new 0-cells on the 1-cells of C_2 and separating the 2-cells into new 2-cells by 1-cells, it follows from the theorem just proved that any regular subdivision of C_2 is such that

$$r_2 = \alpha_2 - 1$$

if and only if C_2 has this property.

59. If C_2 is a 2-circuit and G_2 is any 2-circuit homeomorphic with C_2 , let K_2 be the 2-circuit on C_2 whose cells are respectively homeomorphic with the cells of G_2 . As in § 50 C_2 and K_2 may be regularly subdivided into \bar{C}_2 and \bar{K}_2 and a set of spheres S_2^p constructed such that the sum (mod. 2) of \bar{K}_2 and the 2-circuits defining these spheres is \bar{C}_2 . For each 2-cell k_p^2 of \bar{K}_2 there is one and only one sphere S_2^p which has k_p^2 as one of its 2-cells.

If K_2 is such that $r_2 = \alpha_2 - 1$, \bar{K}_2 has the same property, that is to say, some linear combination of the oriented boundaries of its 2-cells sums to zero. Each of the spheres S_2^p obviously has this property also. The set of oriented 1-circuits which can be formed from the boundaries of the 2-cells of \bar{K}_2 and of the spheres S_2^p is therefore subject to one linear relation involving the oriented 1-circuits of \bar{K}_2 and

one analogous linear relation for each of the spheres S_2^p . Since each S_2^p has just one 2-cell in common with \bar{K}_2 , the linear relations corresponding to the spheres S_2^p can be multiplied by integers and added to the linear relation corresponding to \bar{K}_2 in such a way that all terms involving oriented 1-circuits of \bar{K}_2 cancel out, thus giving a linear relation, R , among oriented 1-circuits bounding 2-cells of the spheres S_2^p which does not involve any oriented 1-circuit bounding a 2-cell of K_2 .

Among the 2-cells of the spheres S_2^p are the 2-cells b_i^2 each determined as explained in § 41 by a 1-cell k_i^1 of \bar{K}_2 . Each such 2-cell is in the spheres S_2^p corresponding to the 2-cells of K_2 incident with the k_i^1 in question, and no others. Since the oriented circuits bounding 2-cells of \bar{K}_2 which are incident with k_i^1 were cancelled out in forming R , the oriented 1-circuit formed from the boundary of b_i^2 is also cancelled out. Hence R contains none of the oriented 1-circuits formed from the boundaries of the 2-cells b_i^2 . Hence R can only contain oriented 1-circuits formed from the boundaries of 2-cells of \bar{C}_2 . It must contain some of these, for otherwise each 2-cell of \bar{C}_2 would be in an even number of spheres S_2^p and hence the sum (mod. 2) of these spheres S_2^p and the complex \bar{K}_2 would be zero contrary to § 51.

Hence the set of oriented 1-circuits formed from the boundaries of the 2-cells of \bar{C}_2 is subject to one linear condition. Hence by § 55 $r_2 = \alpha_2 - 1$ for \bar{C}_2 . Hence by § 58 $r_2 = \alpha_2 - 1$ for C_2 .

60. The theorem of § 53 was that if C_2 is a 2-circuit any complex homeomorphic with C_2 is a 2-circuit. The theorem of the last section adds to this result the theorem that if C_2 is orientable so is also any complex homeomorphic with C_2 . It follows that if one of the complexes into which a manifold can be decomposed is orientable so are all the complexes into which it can be decomposed. Thus the property of orientability or non-orientability is a property of a manifold and is invariant under the group of homeomorphisms.

As a corollary of this it follows that any complex defining a sphere is orientable. The same follows for any sphere

with p handles on observing that the particular complexes used in defining these manifolds are orientable. In like manner, the manifolds defined in § 26 are non-orientable.

Normal Forms for Manifolds

61. It has now been proved that any two homeomorphic manifolds are both orientable or both one-sided, and have the same connectivity. Conversely it can be proved that if two closed manifolds are both orientable (or both one-sided) and have the same connectivity they are homeomorphic. In other words, R_1 and the orientableness of a closed manifold characterize it completely from the point of view of Analysis Situs.

62. By way of establishing this theorem we shall outline a method of reducing any manifold to a normal form. Let C_2 denote a complex whose points constitute a manifold M_2 . Let the 2-cells of C_2 be so ordered that a_k^2 ($k = 2, 3, \dots, \alpha_2$) is incident with at least one 1-cell, say a_{k-1}^1 , which is also incident with one of the 2-cells $a_1^2, a_2^2, \dots, a_{k-1}^2$.

According to § 9 the cells a_1^2, a_1^1, a_2^2 constitute a 2-cell, b_2^2 . Similarly, the cells b_2^2, a_2^1, a_3^2 constitute a 2-cell, b_3^2 . The process may be continued until we arrive at a 2-cell $b_{\alpha_2}^2$ which is made up of all the 2-cells a_i^2 ($i = 1, 2, \dots, \alpha_2$) and of the 1-cells a_j^1 ($j = 1, 2, \dots, \alpha_2 - 1$). The remaining 1-cells are in number $\alpha_1 - \alpha_2 + 1 = \alpha_0 + R_1 - 2$ (§ 30, equation (4)). Hence the boundary of $b_{\alpha_2}^2$ contains $2(\alpha_0 + R_1 - 2)$ 1-cells which coincide by pairs with the 1-cells a_k^1 ($k = \alpha_2, \alpha_2 + 1, \dots, \alpha_1$). We denote by U_1 the linear graph determined by the 1-cells a_k^1 .

63. The graph U_1 has the property that none of its 1-circuits or sets of 1-circuits bounds. For if K_1 were a bounding set of 1-circuits composed of cells of U_1 , then C_2 would be separated by K_1 into two parts, each bounded by K_1 . In the sequence of cells a_i^2 ($i = 1, 2, \dots, \alpha_2$) there must be at least one pair a_j^2, a_{j+1}^2 such that a_j^2 would be in one of the parts in question and a_{j+1}^2 would be in the other. Hence

the 1-cell a_j^1 must be on the common boundary of the two parts, namely K_1 , hence on U_1 . But this would contradict the definition of U_1 as a linear graph containing none of the 1-cells a_j^1 ($j = 1, 2, \dots, \alpha_2 - 1$). Consequently U_1 has the property stated above.

64. The result of the last section may be stated in the following form: Any closed manifold M_2 can be set into continuous correspondence with the points of a convex polygon of $2(\alpha_0 + R_1 - 2)$ edges in a Euclidean plane in such a way that (1) each interior point of the polygon corresponds to and is the correspondent of one point of the manifold; (2) each interior point of an edge of the polygon determines an interior point of another edge such that these two points of the polygon correspond to one point of the manifold, and this point of the manifold corresponds only to these two points of the polygon; (3) each vertex of the polygon determines a set of vertices of the polygon all of which correspond to a single point of the manifold, and this point of the manifold corresponds to these vertices and these only.

65. By a series of transformations on this polygon which involve cutting it by 1-cells running from one vertex to another and piecing it together along corresponding edges, it can be changed into a polygon of $2(R_1 - 1)$ sides all of whose vertices correspond to a single 0-cell of M_2 . This polygon in turn can be transformed into one of three normal forms. If the polygon reduces to the first of these forms the manifold is a sphere with p handles; if the polygon takes the second form, the manifold is a one-sided manifold of the first kind; and if the polygon takes the third form, the manifold is a one-sided manifold of the second kind. Thus, every closed manifold M_2 is of one of the three types described in §§ 25 and 26.

A proof of this theorem which follows the line of argument outlined above is to be found in a paper by H. R. Brahana in the Annals of Mathematics (2), Vol. 23 (1921), pp. 144-68.

CHAPTER III

COMPLEXES AND MANIFOLDS OF n DIMENSIONS

Fundamental Definitions

1. In a Euclidean three-space, four non-coplanar points together with the one- and two-dimensional simplexes (§ 1, Chap. I and § 1, Chap. II) of which they are vertices constitute the boundary of a finite region, called a *three-dimensional simplex* or *tetrahedral region*, of which the four given points are called the *vertices*. The points of the boundary are not regarded as points of the simplex.

A set of $n + 1$ points, not all in the same $(n - 1)$ space, together with the one-, two-, \dots , $(n - 1)$ -dimensional simplexes of which they are vertices constitute the boundary of a finite region in the n -space containing the $n + 1$ points. This region is called an *n-dimensional simplex* and the $n + 1$ given points are called its vertices. The points of the boundary are not regarded as points of the simplex.

Consider any set of objects in (1-1) correspondence with the points of an n -dimensional simplex ($n > 0$) and its boundary. The objects corresponding to the points of the simplex constitute what is called an *n-dimensional cell* or *n-cell*, and those corresponding to the boundary of the simplex what is called the *boundary of the cell*.

The remarks of § 2, Chap. I are now to be applied without change to the n -dimensional case.

2. An n -dimensional complex is defined by the following recursive statements:

An *n-dimensional complex* C_n consists of an $(n - 1)$ -dimensional complex C_{n-1} together with a number, α_n , of n -cells whose boundaries are circuits of C_{n-1} , such that no n -cell has a point in common with another n -cell or with C_{n-1} and such

the 1-cell a_j^1 must be on the common boundary of the two parts, namely K_1 , hence on U_1 . But this would contradict the definition of U_1 as a linear graph containing none of the 1-cells a_j^1 ($j = 1, 2, \dots, \alpha_2 - 1$). Consequently U_1 has the property stated above.

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The remarks of § 2, Chap. I are now to be applied without change to the n -dimensional case.

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that each $(n - 1)$ -cell of C_{n-1} is on the boundary of at least one n -cell. The order relations of the points of the boundary of each n -cell coincide with the order relations among these points regarded as belonging to the $(n - 1)$ -dimensional circuit.* The $(n - k)$ -cells ($k = 1, 2, \dots, n$) on the boundary of an n -cell of C_n are said to be *incident* with it and it is said to be *incident* with them.

An *n-dimensional circuit* or *n-circuit* or *generalized n-dimensional polyhedron* is an n -dimensional complex C_n such that (1) each $(n - 1)$ -cell of C_n is incident with an even number of n -cells and (2) no subset of the cells which constitute C_n satisfies (1).

The definition of *homeomorphism* and the remarks in § 3, Chap. II generalize directly to n dimensions. In particular, *any theorem about an n-dimensional complex which remains valid if the complex is subjected to any (1-1) continuous transformation is a theorem of Analysis Situs.*

An arbitrary subset of the cells of an n -dimensional complex is sometimes referred to as a *generalized n-dimensional complex*, provided it contains at least one n -cell.

3. The definition of a singular or non-singular generalized complex C_k on a complex C_n is a direct generalization of that given in § 33, Chap. II. It is obtained from the definition in Chap. II by substituting C_k for C' , C_n for C_2 and making corresponding substitutions wherever the dimensionality of cells or complexes is mentioned. The number k may be greater than, equal to, or less than n .

It is important to notice that in the fundamental definitions

* This statement can also be put in the following form: Suppose that an i -cell a' appears on the boundaries of two $(i + k)$ -cells, a_1^{i+k} and a_2^{i+k} . Then a_1^{i+k} and a_2^{i+k} and their boundaries are, by definition, in (1-1) correspondences T_1 and T_2 with two $(i + k)$ -dimensional simplexes, b and c and their boundaries. In the correspondence T_1 a' corresponds to an i -dimensional cell b' of the boundary of b while in the correspondence T_2 it corresponds to an i -dimensional cell c' of the boundary of c . The resultant of the correspondences effected by T_1^{-1} and T_2 on b' and a' respectively is a correspondence in which b' corresponds to c' . *This correspondence must be continuous.*

in the two sections above all the cells and the circuits bounding them are non-singular. This insures that the representation by matrices given below shall be unique. It does not, however, exclude the possibility of extending the use of the matrices to cases where, as in § 32, Chap. II, the cells have singular boundaries. But in proving our general theorems we stick to the case of non-singular cells with non-singular boundaries.

Matrices of Incidence

4. Let α_k ($k = 0, 1, \dots, n$) denote the number of k -cells in a complex C_n . The k -cells themselves may be denoted by $\alpha_1^k, \alpha_2^k, \dots, \alpha_{\alpha_k}^k$. The incidence relations between the $(k - 1)$ -cells and the k -cells are represented by a matrix

$$\|\eta_{ij}^k\| = H_k \quad (k = 1, 2, \dots, n)$$

in which $\eta_{ij}^k = 1$ if α_i^{k-1} is incident with α_j^k and $\eta_{ij}^k = 0$ if α_i^{k-1} is not incident with α_j^k . The matrix H_k has α_{k-1} rows and α_k columns.

An n -dimensional complex is completely described by the set of matrices,

$$H_1, H_2, \dots, H_n,$$

for, as can be shown by an obvious argument (cf. § 6, Chap. II) any two complexes having the same set of matrices are in (1-1) continuous correspondence.

The elements of the matrices are combined as integers reduced modulo 2, just as in Chap. I. The ranks of the matrices are denoted by e_1, e_2, \dots, e_n respectively.

By the general theory of such matrices, there exists for each H_k a pair of square matrices A_{k-1}, B_k , of α_{k-1} and α_k rows respectively, each having its determinant equal to 1, such that

$$A_{k-1}^{-1} \cdot H_k \cdot B_k = H_k^*$$

where H_k^* is a matrix of α_{k-1} rows and α_k columns in which the first e_k elements of the main diagonal are unity and all the rest of the elements are zero. Thus the theory of the

n-dimensional complex will involve the matrices $H_i, A_{i-1}, B_i, H_i^*, (i = 1, 2, \dots, n)$.

5. Special cases to illustrate the incidence matrices are easily constructed. For example the matrices for a complex obtained by subdividing a projective 3-space into cells are given in Chap. IX, Vol. II of the Veblen and Young Projective Geometry. The following definition gives another example.

By an *n*-dimensional sphere or a simple closed manifold of *n* dimensions is meant the set of points on a complex whose matrices of incidence are

$$H_1 = H_2 = \dots = H_n = \begin{vmatrix} 1 & 1 \\ 1 & 1 \end{vmatrix}.$$

The *n*-dimensional sphere is easily seen to be homeomorphic with the boundary of an $(n+1)$ -cell. Since it has two 0-cells, two 1-cells, ..., two *n*-cells, its characteristic,

$$\alpha_0 - \alpha_1 + \alpha_2 - \dots + (-1)^n \alpha_n,$$

is 0 if *n* is odd and 2 if *n* is even.

6. Any set of the *k*-cells, $a_1^k, a_2^k, \dots, a_{\alpha_k}^k$, and also the *k*-dimensional complex consisting of a set of *k*-cells and their boundaries, may be denoted by a symbol $(x_1, x_2, \dots, x_{\alpha_k})$, in which $x_i = 1$ if a_i^k is in the set and $x_i = 0$ if a_i^k is not in the set.

These symbols can be added (mod. 2) by precisely the rule given in §§ 14 and 15, Chap. I, for the 0- and 1-dimensional cases. Corresponding to this we have a rule for the addition of two *k*-dimensional complexes consisting each of a set of *k*-cells and their boundaries. The sum, modulo 2, of two *n*-dimensional complexes C'_n and C''_n each of which is a sub-complex of a given complex C_n , is the complex determined by the set of all *k*-cells in C'_n or C''_n but not in both C'_n and C''_n ; it is denoted by $C'_n + C''_n$ (mod. 2). It has the obvious property that if C'_n and C''_n are *n*-circuits, $C'_n + C''_n$ (mod. 2) is also an *n*-circuit or a set of *n*-circuits.

7. The boundary of a *k*-dimensional complex C_k is the $(k-1)$ -dimensional complex consisting of the $(k-1)$ -cells of the

complex C_n which are incident each with an odd number of *k*-cells of C_k , and the boundaries of these $(k-1)$ -cells. Thus a *k*-dimensional complex is a set of *k*-circuits if and only if it has no boundary.

By precisely the same reasoning as that used in the 0- and 1-dimensional cases (cf. § 28, Chap. II) the boundary of a C_k is a $(k-1)$ -dimensional circuit or a set of $(k-1)$ -dimensional circuits having at most a $(k-2)$ -dimensional complex in common. From this reasoning it also follows that every bounding $(k-1)$ -circuit is a sum (mod. 2) of a set of $(k-1)$ -circuits which bound *k*-cells, i. e., which are represented by columns of H_k . Hence all bounding $(k-1)$ -circuits are linearly expressible in terms of those corresponding to a linearly independent set of ρ_k columns of H_k , where ρ_k is the rank of H_k .

8. As in the 0-, 1-, and 2-dimensional cases (cf. § 24, Chap. I),

$$\eta_{i1}^k x_1 + \eta_{i2}^k x_2 + \dots + \eta_{i\alpha_k}^k x_{\alpha_k}$$

is 1 or 0 according as there are an odd or an even number of *k*-cells of the set $(x_1, x_2, \dots, x_{\alpha_k})$ incident with the $(k-1)$ -cell a_i^{k-1} . Hence if

$$(1) \quad H_k \cdot \begin{vmatrix} x_1 \\ x_2 \\ \vdots \\ x_{\alpha_k} \end{vmatrix} = \begin{vmatrix} y_1 \\ y_2 \\ \vdots \\ y_{\alpha_{k-1}} \end{vmatrix},$$

$(y_1, y_2, \dots, y_{\alpha_{k-1}})$ represents the boundary of $(x_1, x_2, \dots, x_{\alpha_k})$.

As a corollary it follows that the *k*-circuits are the solutions of the equations

$$(H_k) \quad \sum_{j=1}^{\alpha_k} \eta_{ij}^k x_j = 0 \quad (i = 1, 2, \dots, \alpha_{k-1}).$$

Since the columns of the matrix H_k represent $(k-1)$ -circuits they represent solutions of the equations

$$(H_{k-1}) \quad \sum_{j=1}^{\alpha_{k-1}} \eta_{ij}^{k-1} x_j = 0 \quad (i = 1, 2, \dots, \alpha_{k-2})$$

and hence

$$(2) \quad H_{k-1} \cdot H_k = 0 \quad (k = 1, 2, \dots, n).$$

The Connectivities R_i

9. If ρ_k denotes the rank of H_k (mod. 2) the number of solutions of the linear homogeneous equations (H_k) in a complete set is $\alpha_k - \rho_k$ (cf. § 25, Chap. I). According to § 8, the columns of H_{k+1} are solutions of the equations (H_k) and hence ρ_{k+1} of these columns can enter in a complete set of solutions of (H_k).

Let $R_k - 1$ be the smallest number of non-bounding k -circuits which it is necessary to adjoin to a set of ρ_{k+1} linearly independent bounding k -circuits in order to have a set of k -circuits on which all others are linearly dependent.

Then for an n -dimensional complex C_n the number of solutions of (H_k) in a complete set is $\rho_{k+1} + R_k - 1$ if $0 < k < n$. Hence

$$\alpha_k - \rho_k = \rho_{k+1} + R_k - 1 \quad (0 < k < n)$$

and

$$\alpha_n - \rho_n = R_n - 1.$$

By § 20, Chap. I

$$\alpha_0 - \rho_1 = R_0.$$

Hence we have the series of equations

$$(1) \quad \begin{array}{r} R_0 - 1 = \alpha_0 - \rho_1 - 1, \\ R_1 - 1 = \alpha_1 - \rho_2 - \rho_2, \\ R_2 - 1 = \alpha_2 - \rho_3 - \rho_3, \\ \vdots \\ R_{n-1} - 1 = \alpha_{n-1} - \rho_n - \rho_n, \\ R_n - 1 = \alpha_n - \rho_n. \end{array}$$

On multiplying these equations alternately by $+1$ and -1 and adding we obtain

$$(2) \quad \sum_{i=0}^n (-1)^i \alpha_i = 1 + \sum_{i=0}^n (-1)^i (R_i - 1).$$

In case the complex C_n is an n -circuit, $R_0 = 1$, $R_n = 2$ and (2) becomes

$$(3) \quad \sum_{i=0}^n (-1)^i \alpha_i = 1 + (-1)^n + \sum_{i=1}^{n-1} (-1)^i (R_i - 1).$$

This is a generalization of Euler's formula (§ 30, Chap. II) to n dimensions. If n is even it reduces to

$$(4) \quad \alpha_0 - \alpha_1 + \alpha_2 - \dots + \alpha_n = 3 - R_1 + R_2 - \dots - R_{n-1}.$$

In case C_n is a manifold and n is odd, (3) when combined with a result obtained in § 29 below reduces to

$$(5) \quad \alpha_0 - \alpha_1 + \alpha_2 - \dots - \alpha_n = 0.$$

10. The number $\alpha_0 - \alpha_1 + \dots + (-1)^n \alpha_n$ is called the *characteristic* of the complex C_n . The number R_i ($i = 0, 1, 2, \dots, n$) is called the *connectivity of the i th order*.

It will presently be proved that the connectivity numbers R_0, R_1, \dots, R_n are Analysis Situs invariants. From this it will follow that the characteristic is also an invariant.

Reduction of the Matrices H_k to Normal Form

11. Let us now consider the matrices A_{k-1} and B_k by which H_k is reduced to its normal form, i. e., the square matrices of determinant 1 such that

$$(1) \quad A_{k-1}^{-1} \cdot H_k \cdot B_k = H_k^*$$

where the first ρ_k elements of the main diagonal of H_k^* are 1 and all the other elements of H_k^* are 0. The existence of these matrices follows from the general theory of matrices (cf. § 49, Chap. I) and we shall show that they can be so chosen as to satisfy certain additional conditions analogous to those found in §§ 30-32, Chap. I.

Writing (1) in the form

$$(2) \quad H_k \cdot B_k = A_{k-1} \cdot H_k^*$$

it follows from § 8 that each of the first q_k columns of B_k represents a k -dimensional complex bounded by the $(k-1)$ -dimensional complex represented by the corresponding columns of A_{k-1} . Each of the remaining $\alpha_k - q_k$ columns of B_k represents a k -dimensional complex which has no boundary, i. e., a k -dimensional circuit or set of circuits.

Since B_k is a square matrix of α_k rows whose determinant is 1, every symbol of the form $(x_1, x_2, \dots, x_{\alpha_k})$ in which the elements are reduced modulo 2 is expressible as a linear combination of the columns of B_k . Hence the symbol for any k -dimensional complex determined by k -cells of C_n is expressible in terms of the columns of B_k . Moreover since the last $\alpha_k - q_k$ columns of B_k are linearly independent and the symbols for all k -circuits are linearly dependent on $\alpha_k - q_k$ of them, the last $\alpha_k - q_k$ columns of B_k are a complete set of k -circuits or sets of k -circuits.

Thus the reduction of the incidence matrices to normal form affords an explicit method of determining the bounding and non-bounding sets of circuits of all dimensionalities.

12. The equation (2) remains valid if we add a given column of B_k to another column of B_k and perform the corresponding operation on the columns of $A_{k-1} \cdot H_k^*$. Hence in particular we may replace any one of the last $\alpha_k - q_k$ columns of B_k by any linear combination of these columns (hence by any symbol for a set of k -circuits) without modifying the right member of (2) since all the last $\alpha_k - q_k$ columns of $A_{k-1} \cdot H_k^*$ are composed of zeros.

13. Suppose we change B_{k-1} by replacing its last q_k columns by the first q_k columns of A_{k-1} , and replacing the preceding $\alpha_{k-1} - q_{k-1} - q_k$ columns by the symbols for a set of $(k-1)$ -circuits no combination of which bounds, the existence of which follows from § 9. By § 12 such a change will leave (2) still valid; hence to show that it is permissible it is sufficient to prove that the new B_{k-1} has determinant 1.

We now have the columns of the new B_{k-1} in three blocks of which the first is the same as for the old B_{k-1} . The symbol for any $(k-1)$ -dimensional complex is a sum of

columns of this first block and a symbol for a set of $(k-1)$ -circuits, as follows from the structure of the original B_{k-1} . Now the columns of the last two blocks are linearly independent (mod. 2) as follows from their choice, and since they number $\alpha_{k-1} - q_{k-1}$ it follows from § 9 that the symbol for any set of $(k-1)$ -circuits is a sum of these columns.

Thus the symbol for any $(k-1)$ -dimensional complex is a sum of columns of the new B_{k-1} . Consequently the determinant of the new B_{k-1} must be 1 (mod. 2), and the change proposed above can be made. Let this be done for all values of k from 1 to n . The last q_k columns of B_{k-1} then represent bounding sets of $(k-1)$ -circuits and the $R_{k-1} - 1$ columns preceding these represent non-bounding $(k-1)$ -circuits.

Since all rows of H_k^* after the q_k th contain only zeros the last $\alpha_{k-1} - q_k$ columns of A_{k-1} are arbitrary subject to the condition that the determinant of A_{k-1} shall be 1. Hence these columns of A_{k-1} may be taken as identical with the first $q_{k-1} + R_{k-1} - 1$ columns of B_{k-1} . Let this be done for all values of k from 1 to n .

14. By this process it is brought about that the matrices A_k are identical with the matrices B_k except for a permutation of columns. The columns of each matrix B_k fall into three blocks. The first q_k columns represent single k -dimensional complexes bounded by sets of $(k-1)$ -circuits. Each of the next $R_k - 1$ columns represents a single non-bounding k -circuit. The last q_{k+1} columns represent bounding sets of k -circuits.

Congruences and Homologies, Modulo 2

15. The definition of congruences and homologies modulo 2 which was made in §§ 37, 38, Chap. II, applies without change to the n -dimensional case. Thus

$$(1) \quad C_k \equiv C_{k-1} \pmod{2}$$

means that C_{k-1} is the boundary of C_k ; and with reference to a complex C_n

$$(2) \quad C_{k-1} \sim 0 \pmod{2}$$

means that there exists a complex C_k on C_n which satisfies the congruence (1). The remarks about linear combination

of congruences and complexes made in Chap. II apply here without change.

All the relations stated above by means of the matrices H_k can also be expressed in terms of congruences and homologies. For if we let a_j^k ($j = 1, 2, \dots, \alpha_k; k = 1, 2, \dots, n$) represent the cell a_j^k and its boundary, instead of the cell alone as in the notation heretofore used, we have the congruences*

$$(3) \quad a_j^k \equiv \sum_{i=1}^{\alpha_{k-1}} \eta_{ij}^k a_i^{k-1} \pmod{2}$$

in which η_{ij}^k are the elements of the matrix H_k . These congruences, which state the incidence relations of the complex C_n , are called the *fundamental congruences (mod. 2)*.

16. If C_k is the complex represented by $(x_1, x_2, \dots, x_{\alpha_k})$ and C_{k-1} the set of $(k-1)$ -circuits represented by $(y_1, y_2, \dots, y_{\alpha_{k-1}})$, the congruence (1) is equivalent to the matrix equation (1) of § 8. The result of reducing the incidence matrices to normal form as summarized in § 14 therefore amounts to the statement that the fundamental congruences are equivalent to the following set of congruences and homologies

$$(4) \quad \begin{array}{l} K_k^{-1} \\ \cdot \\ \cdot \\ K_k^{q_k} \\ C_k^1 \\ \cdot \\ \cdot \\ C_k^{R_{k-1}} \\ C_k^{R_k} \\ \cdot \\ \cdot \\ C_k^{R_k + q_{k+1} - 1} \end{array} \begin{array}{l} \equiv C_{k-1}^{R_{k-1}} \\ \cdot \\ \cdot \\ \equiv C_{k-1}^{R_{k-1} + q_k - 1} \\ \equiv 0 \\ \cdot \\ \cdot \\ \equiv 0 \\ \sim 0 \\ \cdot \\ \cdot \\ \sim 0 \end{array} \pmod{2}$$

* We are here making the obvious convention that $\eta a_i^{k-1} = a_i^{k-1}$ if $\eta = 1$ and $\eta a_i^{k-1} = 0$ if $\eta = 0$.

The further study of these congruences and homologies will involve proving (1) that the k -circuits $C_k^1, C_k^2, \dots, C_k^{R_{k-1}}$ are not homologous to zero (mod. 2) and (2) that every k -circuit on C_n is homologous to a combination of them. With regard to the statement (1) the discussion up to the present shows that no combination of these k -circuits bounds any complex composed of cells of C_n . And with regard to (2) we know that every k -circuit composed of cells of C_n is homologous to a combination of $C_k^1, C_k^2, \dots, C_k^{R_{k-1}}$. To bring complexes on C_n which are not composed of cells of C_n into consideration it will be necessary to go beyond the combinatorial properties of C_n and make use of the geometrical properties of the cells.

Theory of the *n*-Cell

17. The combinatorial properties of a complex C_n which have been discussed above have an elementary application in the theory of the subdivision of a Euclidean space by generalized polyhedra. A system of $(n-1)$ -spaces in an n -space subdivide the n -space into a set of n -dimensional convex regions. They intersect in a number of $(n-2)$ -spaces which subdivide each $(n-1)$ -space into a set of $(n-1)$ -dimensional convex regions which bound the n -dimensional convex regions. The $(n-2)$ -spaces have $(n-3)$ -spaces in common which divide the $(n-2)$ -spaces into convex regions, and so on. Thus the set of $(n-1)$ -spaces defines a subdivision of the n -space into a set of cells which can be treated by the methods described above. Any k -circuit formed from the k -dimensional convex regions is a generalized polyhedron. Any such k -circuit bounds a $(k+1)$ -dimensional complex composed of convex $(k+1)$ -cells.

A treatment of the theory of polyhedra from this point of view by the author is to be found in the Transactions of the American Math. Soc., Vol. 14 (1913), p. 65. (See also the correction Vol. 15, p. 506.) Earlier and later treatments without the machinery used here are to be found in the papers by N. J. Lennes, Am. Journ. of Math., Vol. 33 (1911),

p. 37, and Lilly Hahn, Monatshefte für Math. u. Phys., Vol. 25 (1914), p. 303. Since an n -cell is homeomorphic with a Euclidean space all this is the most elementary part of the theory of the n -cell.

18. As in § 8, Chap. II, we can define a system of curves in any n -cell a_i^n ($i = 1, 2, \dots, \alpha_n$) which have the properties of the system of straight lines interior to a simplex in a Euclidean space. It is only necessary to set up a (1-1) continuous correspondence F_i between the interior and boundary of the n -cell and the interior and boundary of a simplex and to regard as *straight* those curves in the n -cell which are images of straight lines in the simplex.

Under these definitions any two points of an n -cell or its boundary determine a straight 1-cell joining them; any three non-collinear points determine a straight 2-cell bounded by them and the three straight 1-cells which they determine by pairs; in general, any $i+1$ points ($i = 1, 2, \dots, n$) determine a straight i -dimensional simplex bounded by the straight j dimensional simplexes ($j = 0, 1, 2, \dots, i$) determined by subsets of the i points.

19. From the separation theorems on Euclidean polyhedra (§ 17) there follow at once the following important corollaries, which are all to be understood as referring to complexes composed of "straight" cells:

If S_{n-2} is an $(n-2)$ -dimensional sphere on the boundary of an n -cell a^n the boundary of a^n consists of S_{n-2} and two $(n-1)$ -cells a_1^{n-1} and a_2^{n-1} . Any $(n-1)$ -cell a_3^{n-1} contained in a^n and bounded by S_{n-2} separates a^n into two n -cells, one bounded by a_1^{n-1} , S_{n-2} , and a_3^{n-1} and the other bounded by a_2^{n-1} , S_{n-2} , and a_3^{n-1} . There are an infinity of non-singular $(n-1)$ -cells contained in a^n and bounded by S_{n-2} .

If two n -cells a_1^n , a_2^n are incident with an $(n-1)$ -cell a^{n-1} and have no common point they and a^{n-1} constitute an n -cell b^n . If their boundaries have nothing in common except a^{n-1} and its boundary the boundary of b^n is the sum (mod. 2) of their boundaries.

This proposition is a special case of the following theorem: If a set of n -cells, $(n+1)$ -cells, \dots , $(n+p)$ -cells are all incident with an $(n-1)$ -cell a^{n-1} and are such that the incidence relations between the $(n+i)$ -cells ($i = 0, 1, 2, \dots, p-1$) and the $(n+i+1)$ cells are the same as those between the i -cells and $(i+1)$ -cells of a p -dimensional sphere, the set of all points on a^{n-1} and the cells incident with it constitute an $(n+p)$ -cell.

The set of all cells of a complex C_n which are incident with an i -cell a^i and of higher dimensionality than a^i constitute, with a^i itself, what is called a *star of cells*. If the incidence relations among the cells of a star satisfy the conditions described in the paragraph above the star is said to be *simply connected*. If a^{i+p} is one cell of a star, a^{i+p} and all cells of the star of dimensionality greater than $i+p$ which are incident with a^{i+p} constitute a star of cells.

These theorems all remain valid if the restriction to straight cells is dropped. In this more general form they depend on the generalizations to n dimensions of the Jordan and Schoenflies theorems quoted in § 10, Chap. II. The generalized Jordan theorem has been proved by L. E. J. Brouwer, Math. Ann., Vol. 71 (1911), p. 37 but the generalized Schoenflies theorem is still unproved. As in the two-dimensional case, we shall get along with the restricted form of these theorems.

Regular Complexes

20. Just as in Chap. II it was found convenient to decompose a complex into generalized triangles, here it will be found convenient to consider complexes whose n -cells are generalized simplexes. A complex is said to be *regular* if (1) each n -cell a_j^n is in such a (1-1) continuous correspondence with a simplex that each 0-cell incident with a_j^n corresponds to a vertex of the simplex, each 1-cell incident with a_j^n to an edge of the simplex and in general each i -cell ($i = 1, 2, \dots, n-1$) incident with a_j^n corresponds to an i -dimensional simplex of the boundary of the simplex and (2) no set of $i+1$ 0-cells are the vertices of more than one i -cell of the complex.

It has been shown in Chap. II how to decompose any 2-dimensional complex C_2 into a regular complex \bar{C}_2 . This process will now be generalized as follows:

For convenience in phraseology, let a definition of straightness be introduced for all the 2-cells of C_n in the fashion of § 18. Then let a definition of straightness be introduced for all the 3-cells, which definition may be entirely unrelated to the one used for the 2-cells. And in general let a definition of straightness be introduced for each i -cell ($i = 2, 3, \dots, n$) quite independently of that used for all other cells.

Let $P_j^0 = \alpha_j^0$ ($j = 1, 2, \dots, \alpha_0$) and let P_j^i be an arbitrary point interior to the cell a_j^i ($i = 1, 2, \dots, n; j = 1, 2, \dots, \alpha_i$). The points P_j^i ($i = 0, 1, 2, \dots, n; j = 1, 2, \dots, \alpha_i$) are the vertices of \bar{C}_n . The 1-cells of C_n are the straight 1-cells joining every point P_j^i ($i = 1, 2, \dots, n; j = 1, 2, \dots, \alpha_i$) to every vertex of C_n on the boundary of a_j^i . A 2-cell of \bar{C}_n is the set of points on all straight 1-cells joining a point P_j^i ($i = 2, 3, \dots, n; j = 1, 2, \dots, \alpha_i$) to the points of a 1-cell of \bar{C}_n on the boundary of a_j^i . Each of these 2-cells is bounded by just three 1-cells of C_n .

Continuing this process step by step we obtain the 3-cells, 4-cells, \dots , n -cells of \bar{C}_n . A k -cell of \bar{C}_n is the set of points on all straight 1-cells joining a point P_j^i ($i = k, k+1, \dots, n; j = 1, 2, \dots, \alpha_i$) to the points of a $(k-1)$ -cell of \bar{C}_n on the boundary of a_j^i . Each k -cell so defined is evidently bounded by $k+1$ $(k-1)$ -cells.

The complex C_n thus defined is called a *regular subdivision* of C_n .

21. No two 0-cells of \bar{C}_n are joined by more than one 1-cell. Hence any 1-cell of C_n may be denoted by $P_k^i P_l^j$ ($i < j$). In like manner no m 0-cells ($2 \leq m \leq n+1$) are vertices of more than one $(m-1)$ -cell of C_n . Hence any such cell may be denoted by its vertices $P_q^i P_r^j \dots P_s^s$. These vertices are by construction all on cells of C_n of different dimensionality. Hence they may always be taken in such an order that $i < j < \dots < s$.

Incidentally it may be remarked here that on account of the properties just referred to, \bar{C}_n may be described by means of a matrix giving the incidence relations between its n -cells and 0-cells. Also, it can be set into (1-1) continuous correspondence with a set of cells of a simplex in a Euclidean space of a sufficiently high number of dimensions. For these propositions, see the Annals of Mathematics, Vol. 14 (1913), pp. 175-177. The correspondence with cells of a Euclidean simplex can be used to introduce such a definition of distance and straightness in \bar{C}_n that the straightness and distance of any cell is in agreement with the straightness and distance of any cell with which it is incident.

22. The relationship between the complexes C_n and \bar{C}_n may be stated as follows:

(1) Each n -cell of C_n , a_i^n , is the sum (mod. 2) of all n -cells $P_a^0 P_b^1 \dots P_i^n$ of \bar{C}_n having P_i^n as a vertex.*

⋮

⋮

($n-k+1$) Each k -cell of C_n , a_i^k , is the sum (mod. 2) of all k -cells $P_a^0 P_b^1 \dots P_i^k$ of \bar{C}_n which have P_i^k as a vertex (the superscripts are all less than or equal to k).

⋮

⋮

($n+1$) Each 0-cell of C_n , a_i^0 is the 0-cell P_i^0 .

23. The values of R_1, R_2, \dots, R_n determined from C_n are the same as those determined from \bar{C}_n . In order to prove this, consider any i -circuit K_i of \bar{C}_n which is not simply a subdivision of an i -circuit of C_n , and which therefore contains at least one of the points P_j^m , $m > i$. We choose such a point for which m has its maximum value. The i -cells of K_i which are incident with P_j^m are then incident with $(i-1)$ -cells of the boundary of the cell a_j^m of C_n . These $(i-1)$ -cells of the boundary of a_j^m constitute one or more $(i-1)$ -circuits K_{i-1}^a because the $(i-1)$ -cells of K_i which are incident with

* The sum (mod. 2) of a set of k -cells of a star will be understood to contain the cells of the star that are on the boundaries of the k -cells of the sum.

P_j^m and with $(i - 2)$ -cells of the boundary of a_j^m are incident each with an even number of i -cells of K_i . Now by mathematical induction we may assume the invariance of the connectivity numbers for dimensions less than n , since we shall later establish it for the dimension n (§ 42). Hence K_{i-1}^a bounds at least one i -dimensional complex C_i^a composed of cells of C_n on the boundary of a_j^m . By its definition it also bounds a complex composed of i -cells of K_i which are incident with P_j^m . These two complexes constitute an i -circuit or set of i -circuits K_i^a , which bounds the complex composed of the $(i + 1)$ -cells of \bar{C}_n which are incident with P_j^m and the i -cells of C_i^a . If K_i^a is added (mod. 2) to K_i the resulting set of i -circuits K_i' does not pass through P_j^m . Repeating this argument until there are no longer any vertices $P_j^m, m > i$, of C_n on K_i , it follows that by adding bounding sets of circuits to K_i it can be converted into a set of i -circuits which does not pass through any of the vertices $P_k^m, m > i$, of C_n . Such a set of i -circuits is simply a subdivision of a set of i -circuits of C_n .

From this it follows that all i -circuits of \bar{C}_n are linearly dependent on bounding sets of circuits and circuits coincident with circuits of C_n . Hence the value of R_i determined by \bar{C}_n is not greater than that determined by C_n . It also cannot be less, for if so there would be a linear relation among the i -circuits $C_i^p (p = 1, 2, \dots, R_i - 1)$ regarded as circuits of C_n . But this would mean that there was a complex K_{i+1} composed of cells of \bar{C}_n and bounded by some or all of the circuits C_i^p . By an argument like that in the paragraph above K_{i+1} could be replaced by a complex K_{i+1}' coincident with a complex composed of cells of C_n . But the existence of K_{i+1}' would mean a linear relation among the i -circuits C_i^p regarded as i -circuits of C_n . Hence the value of R_i determined by C_n is not less than that determined by C_n .

Manifolds

24. By a *neighborhood* of any i -cell a^i on a complex C_n is meant any set S of non-singular cells on C_n such that any

set of points of C_n having a limit point on a^i contains points on the cells of S .

If C_n is an n -circuit such that every star of its cells is simply connected, the set of points on C_n is called a closed n -dimensional manifold. It is easily proved that any regular subdivision of such a C_n satisfies the same conditions. This definition implies that every point of a manifold has a neighborhood which is an n -cell. It has not been proved, however, that if a point set satisfies the above conditions for one subdivision into cells, it satisfies them for all other subdivisions into cells.

Dual Complexes

25. A complex C_n' is said to be *dual* to a complex C_n if the incidence relations between the k -cells and $(k - 1)$ -cells of C_n' are the same as those between the $(n - k)$ -cells and $(n - k + 1)$ -cells of C_n for $k = 1, 2, \dots, n$. In case C_n defines a manifold, a complex C_n' dual to C_n can be constructed by first making a regular subdivision of C_n into \bar{C}_n , then defining as an n -cell of C_n' the set of all points on each star of cells of C_n having a vertex of C_n as center; next defining as an $(n - 1)$ -cell of C_n' the set of all points on each star of cells of dimensionality $n - 1$ and less which are incident with the point P_i^1 on a 1-cell of C_n , but are not incident with any P_j^0 , and so on, finally defining as the 0-cells of C_n' the points P_i^n on the n -cells of C_n .

This process is illustrated in Fig. 3, page 44 for the two-dimensional case. In this figure the vertices of C_2' are the points P_i^2 , the 1-cells of C_2' are made up of the pairs of 1-cells $P_i^1 P_j^2, P_i^1 P_k^2$ of \bar{C}_2 , and the 2-cells of C_2' are the triangle stars at the vertices of C_2 .

26. The construction for C_n' may be stated a little more explicitly in terms of our notations (cf. § 22) as follows:

(1) Each 0-cell of C_n' is the 0-cell P_i^n .

⋮

$(n-k+1)$ Each $(n-k)$ -cell of C'_n , b_i^{n-k} , is the sum (mod. 2) of all $(n-k)$ -cells $P_i^k P_j^{k+1} \dots P_p^n$ of \bar{C}_n which have P_i^k as a vertex.

$(n+1)$ Each n -cell of C'_n , b_i^n , is the sum (mod. 2) of all n -cells $P_i^0 P_j^1 \dots P_l^n$ of \bar{C}_n which have P_i^0 as a vertex.

In order to make sure that this actually defines a complex dual to C_n it must be proved first that each of the statements (1) \dots $(n+1)$ defines a cell and second that the set of cells has the properties required of a dual complex.

27. Consider first the statement $(n+1)$. The 0-cell P_i^0 is a vertex a_i^0 of C_n . Since we are dealing with a manifold, a_i^0 and the set of all cells of \bar{C}_n incident with it form a simply connected star, and the set of points on this star form an n -cell. This n -cell we have called b_i^n .

No two of the n -cells b_i^n have a point in common because no n -cell of \bar{C}_n is incident with more than one vertex of C_n (in the notation $P_i^0 P_j^1 \dots P_q^n$ only one superscript is zero). Moreover every point on a cell of C_n is on the interior or boundary of one of the cells b_i^n because each n -cell of \bar{C}_n is incident with at least one vertex of C_n (the superscript zero always appears once in the notation $P_i^0 P_j^1 \dots P_q^n$).

Next consider the statement $(n-k+1)$. The point P_i^k is on the k -cell a_i^k of C_n and this k -cell contains a k -cell $P_a^0 P_b^1 \dots P_i^k$ of \bar{C}_n . Since C_n is a regular subdivision of C_n , $P_a^0 P_b^1 \dots P_i^k$ and the set of all cells of \bar{C}_n of dimensionality $k+1$ or greater which are incident with it form a simply connected star (§§ 19, 24); and the set of all points on the cells of the star forms a single cell which is the sum (mod. 2) of the n -dimensional cells of the star. The n -dimensional cells of the star are all n -cells of \bar{C}_n which can be denoted by $P_a^0 P_b^1 \dots P_i^k P_j^{k+1} \dots P_p^n$ in which the first $k+1$ of the P 's are fixed and the rest are variable. The incidence relations among the cells of this star are by §§ 19, 24 those of an $(n-k-1)$ -dimensional sphere. These incidence relations

are however the same as those among the $(n-k)$ -cells $P_i^k P_j^{k+1} \dots P_p^n$ described in the statement $(n-k+1)$ and the cells of lower dimensionality with which they are incident. Hence the sum, (mod. 2) of the cells $P_i^k P_j^{k+1} \dots P_p^n$ described in the statement $(n-k+1)$ is an $(n-k)$ -cell. This $(n-k)$ -cell we call b_i^{n-k} . It obviously has the point P_i^k , and this point only, in common with a_i^k .

28. Let us next find the incidence relations among the b 's. If a_i^k is incident with a_j^{k+1} , there is a k -cell, $P_a^0 P_b^1 \dots P_i^k$, of \bar{C}_n contained in a_i^k which is incident with the $(k+1)$ -cell, $P_a^0 P_b^1 \dots P_i^k P_j^{k+1}$, contained in a_j^{k+1} . The cell b_i^{n-k} dual to a_i^k is the sum (mod. 2) of all the $(n-k)$ -cells $P_i^k P_j^{k+1} P_l^{k+2} \dots P_s^n$ for the given value of i . The cell b_j^{n-k-1} dual to a_j^{k+1} is the sum (mod. 2) of all the $(n-k-1)$ -cells $P_j^{k+1} P_l^{k+2} \dots P_s^n$ for the given value of j . Since each of the $(n-k-1)$ -cells of \bar{C}_n which enter into b_j^{n-k-1} is incident with an $(n-k)$ -cell of \bar{C}_n contained in b_i^{n-k} it follows that b_i^{n-k} is incident with b_j^{n-k-1} .

Hence if a_i^k is incident with a_j^{k+1} , b_i^{n-k} is incident with b_j^{n-k-1} . The converse proposition is proved in exactly the same way. Hence a_i^k is incident with a_j^{k+1} if and only if b_i^{n-k} is incident with b_j^{n-k-1} .

Duality of the Connectivities R_i

29. Stating this result for the case $k = n-1$, we have that a_i^{n-1} is incident with a_j^n if and only if b_i^1 is incident with b_j^0 . Hence the matrix of incidence relations between the 0-cells and 1-cells of the complex C'_n is the matrix H'_n obtained from the matrix H_n of the complex C_n by interchanging rows and columns. In like manner it is seen that, in general, the matrix of incidence relations between the $(n-k-1)$ -cells and $(n-k)$ -cells of the complex C'_n is the transposed matrix H'_{k+1} of the matrix H_{k+1} of the complex C_n . Hence the matrices of incidence H_1, H_2, \dots, H_n of C'_n are the matrices $H'_n, H'_{n-1}, \dots, H'_1$ of C_n .

The ranks of these matrices are $\varrho_n, \varrho_{n-1}, \dots, \varrho_1$ respectively. Moreover the numbers of 0-cells, 1-cells, \dots , n -cells of C'_n are $\alpha_n, \alpha_{n-1}, \dots, \alpha_1, \alpha_0$ respectively. Hence by the formula for the i -dimensional connectivity R_i , it follows that the 1-, \dots , $(n-1)$ -dimensional connectivities of C'_n are R_{n-1}, \dots, R_1 respectively.

It was shown in § 23 that the connectivity R_i of a complex \bar{C}_n obtained by a regular subdivision of C_n is the same as that of C_n . But by comparing § 22 with § 26 it is seen that \bar{C}_n is a regular subdivision both of C_n and of C'_n . Hence the connectivity R_i of C'_n is the same as that of C_n . Hence $R_{n-1}, R_{n-2}, \dots, R_1$ are the same as R_1, R_2, \dots, R_{n-1} respectively. That is

$$R_{n-k} = R_k \quad (k = 1, 2, \dots, n-1).$$

It should be noted that this duality relation does not apply to R_0 and R_n . In the case of a manifold, which we are considering here, $R_0 = 1$ and $R_n = 2$.

30. An important corollary of this result is that for a manifold of an odd number of dimensions the characteristic is zero. For the equations

$$\alpha_0 - \alpha_1 + \dots + (-1)^n \alpha_n = 1 + (-1)^n + \sum_{i=1}^{n-1} (-1)^i (R_i - 1)$$

and

$$R_i = R_{n-i} \quad (i = 1, 2, \dots, n-1)$$

give

$$\alpha_0 - \alpha_1 + \alpha_2 - \dots - \alpha_n = 0,$$

as already noted in § 9.

Generalized Manifolds

31. The definition of a manifold in § 24 can be generalized as follows: A *generalized manifold* of n dimensions is the set of all points on an n -circuit C_n such that if a^{i-1} is any cell of C_n the incidence relations among the (i) -cells, $(i+1)$ -cells, \dots , $(i+k)$ -cells (where $i+k = n$) incident with a^{i-1} are the same as the incidence relations among the 0-cells, 1-cells, \dots , k -cells of a complex defining a generalized manifold of k dimensions: a generalized manifold of zero dimensions is a 0-circuit.

For $n = 0, 1, 2$, a generalized manifold is the same as a manifold. But for $n \geq 3$ it includes sets of points which are not manifolds in the narrow sense.

32. To bring this out let us consider the following example given in the article on Analysis Situs by Dehn and Heegaard in the Encyclopädie. Let S_4 be a Euclidean space of four dimensions, a^0 a point in S_4 , S_3 a three-space in S_4 but not on a^0 , and M_2 an arbitrary two-dimensional manifold (e. g., an anchor ring) in S_3 . Let M_2 be decomposed into 0-cells, 1-cells and 2-cells constituting a two-dimensional complex, B_2 . The segment joining any 0-cell of B_2 to a^0 is a 1-cell, the points on the segments joining the points of a 1-cell of B_2 to a^0 constitute a 2-cell, and the points on the segments joining the points of a 2-cell of B_2 to a^0 constitute a 3-cell. The complex C_3 composed of all the 1-cells, 2-cells and 3-cells formed by this process, together with a^0 and the cells of B_2 , is such that the boundary of an arbitrarily small neighborhood of a^0 is of the same structure as B_2 . Hence the set of points on each such boundary is a surface like M_2 (e. g., an anchor ring).

It is obvious that a generalized three-dimensional manifold can be constructed which has any number of points with neighborhoods which are not spherical. A generalized four-dimensional manifold can have both 0-cells and 1-cells whose neighborhoods are not simply connected, and so on.

33. It was shown in Chap. II that any 2-circuit can be regarded as a singular manifold. The generalization of this theorem is that any n -circuit is a *singular* (cf. § 3) *generalized manifold*. We shall repeat the process of § 34, Chap. II, for the three-dimensional case, because one new point enters, but shall leave the formal generalization to the reader.

Let C_3 be an arbitrary 3-circuit. Each of its 2-cells a_i^2 is incident with an even number $2n_i$ of 3-cells. These may be grouped in n_i pairs of 3-cells associated with a_i^2 , and the method used in § 34, Chap. II, may be used to obtain a 3-circuit C'_3 whose cells coincide with those of C_3 and which

is such that each of its 2-cells is incident with two and only two of its 3-cells.

The incidence relations between the 2-cells and 3-cells of C'_3 which are incident with a 1-cell a'_j of C'_3 are the same as those of a linear graph in which each 0-cell is incident with just two 1-cells. Since such a linear graph is a set of 1-circuits having no points in common, the 2-cells and 3-cells incident with a'_j fall into a number, n_j , of groups associated with a'_j such that the incidence relations among the cells of a group are those of a 1-circuit. With the aid of these groups, by the method of § 34, Chap. II, a complex C''_3 is defined whose cells coincide with those of C'_3 and which is such that all of its cells of dimensionality greater than i which are incident with any one of its i -cells ($i = 2, 1$) are related among themselves by a set of incidence relations identical with those of a $(2 - i)$ -circuit.

The incidence relations between the 1-cells, 2-cells and 3-cells incident with a 0-cell a'_k of C''_3 now satisfy the same conditions as those between the 0-cells, 1-cells and 2-cells of a number, n_k , of two-dimensional manifolds which have no points in common. Hence they fall into n_k groups associated with a'_k such that the incidence relations among the 1-cells, 2-cells and 3-cells of a group are the same as those among the 0-cells, 1-cells and 2-cells of a two-dimensional manifold. Hence a complex C'''_3 can be defined whose cells coincide with those of C''_3 and which satisfies the definition of a generalized manifold.

C'''_3 will be a manifold in the narrow sense only in the case where each of the groups associated with each vertex a'_k has the incidence relations of the cells of a sphere.

34. Since the boundary of any complex consists of one or more circuits, it consists of one or more generalized manifolds any or all of which may be singular.

Bounding and Non-bounding Sets of k -Circuits

35. Let us now take up the problem: Given a set of k -circuits C_k on a complex C_n , to determine whether or not

there exists a $(k + 1)$ -dimensional complex, singular or not, on C_n which is bounded by C_k . This is the problem solved in Chap. II (cf. § 35) for the case where $n = 2$ and $k = 1$. As the problem is now formulated k may be less than, equal to, or greater than n , and C_k may have singularities of any degree of complexity compatible with the definition in § 3.

The solution of the problem in the simplest case is contained in the following obvious theorem which is a direct generalization of that given in § 36, Chap. II: Any sphere of k dimensions on an n -cell a^n is the boundary of a $(k + 1)$ -cell on a^n . The $(k + 1)$ -cell can be constructed by joining an arbitrary point, P , of a^n to all the points of the k -dimensional sphere by straight 1-cells or, in case of points of the sphere which coincide with P , by singular 1-cells coincident with P . The solution of our problem for the general case which we shall now develop is entirely parallel to that carried out in §§ 39 to 46, Chap. II.

36. Let K_i be an i -dimensional complex on C_n . Let \bar{C}_n be a regular sub-division of C_n . Let a definition of distance and straightness be introduced relative to \bar{C}_n and let all references to distance and straightness in the rest of this argument be understood to refer to this definition. Let \bar{C}_n be a regular subdivision of \bar{C}_n . By simple continuity considerations it can be proved that K_i can be regularly subdivided into a complex \bar{K}_i such that for each j -cell of K_i there is a star of cells of \bar{C}_n to which it is interior. A correspondence A is now defined as a correspondence between the vertices of \bar{K}_i and those of \bar{C}_n by which each vertex of \bar{K}_i which is interior to a star of cells of \bar{C}_n having a vertex of \bar{C}_n as center corresponds to that vertex of \bar{C}_n , and by which each vertex of \bar{K}_i which is on the boundary of two or more stars of cells of \bar{C}_n having vertices of \bar{C}_n as centers corresponds to one of these vertices of \bar{C}_n .

Since every point of C_n is on or on the boundary of some star of cells of \bar{C}_n with center at a vertex of \bar{C}_n , a correspondence A determines a unique vertex of \bar{C}_n for each vertex of \bar{K}_i . Moreover since any cell of \bar{K}_i is on a star of cells

of \bar{C}_n its vertices correspond to vertices of a single cell of \bar{C}_n . Hence the correspondence *A* makes each cell of \bar{K}_i correspond to a cell of \bar{C}_n of the same or lower dimensionality.

37. Let the *r*-cells of \bar{C}_n be denoted by c_j^r ($r = 0, 1, 2, \dots, n$; $j = 1, 2, \dots, \alpha_r$) and those of \bar{K}_i by k_j^r ($r = 0, 1, 2, \dots, i$; $j = 1, 2, \dots, \beta_r$). Each 0-cell k_j^0 of \bar{K}_i can be joined to the 0-cell of \bar{C}_n to which it corresponds under the correspondence *A* by a straight 1-cell b_j^1 ; or, if k_j^0 coincides with the point to which it corresponds, by a singular 1-cell b_j^1 coinciding with k_j^0 . Similarly, for each 1-cell k_j^1 of \bar{K}_i , a 2-cell b_j^2 can be constructed by joining each point of k_j^1 to a point of the corresponding cell of \bar{C}_n by a 1-cell which is either straight or coincident with a point. By a similar construction there is determined for every cell k_j^r of \bar{K}_i a cell b_j^{r+1} composed of 1-cells joining points of k_j^r to points of the cell of \bar{C}_n to which k_j^r corresponds under the correspondence *A*. The $(i+1)$ -dimensional complex composed of the cells b_j^{i+1} and their boundaries is denoted by B_{i+1} . It is such that the incidence relations of b_p^{r+1} and b_q^r are the same as those of k_p^r and k_q^{r-1} .

38. If K_i is a set of *i*-circuits, all *i*-cells b_j^i ($j = 1, 2, \dots, \beta_{i-1}$) must cancel out when the boundaries of the $(i+1)$ -cells b_j^{i+1} ($j = 1, 2, \dots, \beta_i$) are added together (mod. 2). Hence the boundary of B_{i+1} consists either of \bar{K}_i alone or of \bar{K}_i and a set of *i*-circuits K_i' composed of cells of \bar{C}_n . That is to say

$$(1) \quad B_{i+1} \equiv \bar{K}_i + K_i' \pmod{2}$$

and

$$\bar{K}_i \sim K_i' \pmod{2}$$

where K_i' is either zero or a set of *i*-circuits composed of cells of \bar{C}_n .

There is no difficulty in seeing that any *i*-circuit is homologous (mod. 2) to any regular sub-division of itself. This may be proved by means of a singular $(i+1)$ -dimensional complex which contains, besides the cells of the given *i*-circuit and those of its subdivision, one $(k+1)$ -cell incident with each *k*-cell of the *i*-circuit, $k = 0, 1, \dots, i$. Hence

$$K_i \sim \bar{K}_i$$

and therefore

$$(2) \quad K_i \sim K_i'$$

It is obvious that $K_i' = 0$ if $i > n$. Hence

$$(3) \quad K_{n+r} \sim 0 \pmod{2}$$

whenever $r > 0$.

39. From the homology (2) it follows that $K_i \sim 0$ if and only if $K_i' \sim 0$. By § 7, K_i' bounds a complex composed of cells of \bar{C}_n if and only if it is represented by a symbol $(x_1, x_2, \dots, x_\alpha)$ which is linearly dependent on the columns of the matrix H_{i+1} for \bar{C}_n . We shall now prove that if $K_i' \sim 0$, K_i' bounds a complex composed of cells of \bar{C}_n , from which result it obviously follows that $K_i \sim 0$ if and only if the symbol $(x_1, x_2, \dots, x_\alpha)$ for K_i' is linearly dependent on the columns of H_{i+1} .

40. Given that $K_i' \sim 0$ and that K_i' is composed of cells of \bar{C}_n , let K_{i+1}' be a bounded complex, and let us subdivide K_{i+1}' as above, preparatory to setting up a correspondence *A*. We denote the subdivision by K_{i+1}'' , and the corresponding subdivision of K_i' by K_i'' . Then we will have

$$(4) \quad K_{i+1}'' \equiv K_i'' \pmod{2}.$$

Let us construct a correspondence *A* for K_{i+1}'' exactly as in § 36, and by means of it construct a complex B_{i+2} analogous to the complex B_{i+1} of § 37. When the boundaries of the $(i+2)$ -cells of B_{i+2} are added to K_{i+1}'' (mod. 2), all the $(i+1)$ -cells of B_{i+2} cancel except those determined by the cells k_j^i of the boundary of K_{i+1}'' and certain others which are cells of \bar{C}_n . Let us denote the $(i+1)$ -dimensional complexes determined by these two sets of $(i+1)$ -cells, by G_{i+1} and \bar{K}_{i+1} respectively. This gives the congruence

$$(5) \quad B_{i+2} \equiv K_{i+1}'' + G_{i+1} + \bar{K}_{i+1} \pmod{2},$$

which implies the congruence

$$(6) \quad K_{i+1}'' + G_{i+1} + \bar{K}_{i+1} \equiv 0 \pmod{2}.$$

Since K_i'' is a set of i -circuits, none of the cells of B_{i+2} determined by $(i-1)$ -cells k_j^{i-1} will appear in the boundary of G_{i+1} . Hence we have

$$(7) \quad G_{i+1} \equiv K_i'' + K_i''' \pmod{2},$$

where K_i''' is a set of i -circuits composed of cells of \bar{C}_n . On adding (4), (6) and (7) we obtain

$$(8) \quad K_{i+1} \equiv K_i''' \pmod{2}.$$

Hence the theorem stated in § 39 will be proved if we show that K_i''' is identical with K_i' .

To prove this, let us consider a single i -cell, say c_j^i , of K_i' . The vertices of K_i'' on c_j^i or on its boundary are all assigned to vertices of c_j^i under the correspondence A . Hence the i -cells, say c_{jk}^i , of K_i'' into which c_j^i is subdivided all contribute either nothing or c_j^i itself to the set of i -cells of K_i''' . Now the sum (mod. 2) of the cells identical with c_j^i obtained from the cells c_{jk}^i is bounded by whatever we get by the process applied in the previous paragraphs (to obtain K_i''' from K_i'') when that process is applied to the boundary of c_j^i as subdivided for K_i'' . For that is exactly what we did prove at the end of the last paragraph, with i replaced by $i+1$, and the subdivision of c_j^i replaced by K_{i+1}'' . But by mathematical induction we may assume that the boundary thus obtained is exactly the boundary of c_j^i as composed of cells of K_i' . Hence the sum (mod. 2) of the i -cells identical with c_j^i obtained as just described, being bounded by the boundary of c_j^i , must be exactly c_j^i taken once (mod. 2). Since, then, from the subdivision of every i -cell of K_i' we obtain that same cell of K_i' from the entire subdivision, K_i''' , of K_i' we must obtain K_i' in its entirety. In other words, K_i''' is identical with K_i' , which is what we set out to prove.

41. We now have an explicit method for determining whether a set of i -circuits K_i on C_n does or does not bound. For

a construction has been given to determine the homology (2) of § 38 and $K_i \sim 0$ if and only if K_i' bounds a complex composed of cells of \bar{C}_n .

It is a corollary that no set of n -circuits composed of cells of C_n can satisfy a homology $K_n \sim 0$. For there are no $(n+1)$ -cells in \bar{C}_n . Hence, in particular, a set of n -circuits C_n cannot bound a singular complex on C_n . On the other hand, every $(n+k)$ -circuit ($k > 0$) on C_n bounds an $(n+k+1)$ -dimensional complex on C_n as stated in (3), § 38.

Invariance of the Connectivities R_i

42. We are now ready to prove the invariance of the connectivities R_0, R_1, \dots, R_n under the group of all homeomorphisms. This invariance is obvious for R_0 because R_0 is the number of connected complexes which compose C_n . To prove the invariance of R_i ($i > 0$) for any complex C_n , we first observe that according to § 23, R_i is the same for C_n as for any regular subdivision of C_n . We therefore fix attention on a regular subdivision \bar{C}_n .

By § 9 there exists* a set of i -circuits C_i^j ($j = 1, 2, \dots, R_i - 1$) such that (1) there is no $(i+1)$ -dimensional complex composed of cells of \bar{C}_n which is bounded by any combination of the circuits C_i^j and (2) if C_i^j is any other i -circuit composed of cells of \bar{C}_n it is homologous to the sum (mod. 2) of some or all of the i -circuits C_i^j . By combining (1) with the theorem of § 39 we have at once that: (a) there is no $(i+1)$ -dimensional complex of any sort on C_n which is bounded by any combination of the circuits C_i^j . From (2) and § 38 it follows that: (b) if C_i is any i -circuit on \bar{C}_n it is homologous to a linear combination (mod. 2) of the i -circuits C_i^j ($j = 1, 2, \dots, R_i - 1$). For C_i is homologous either to zero or to an i -circuit C_i^j which is composed of cells of \bar{C}_n , and by (2) C_i^j is homologous to a combination of the i -circuits C_i^j .

From the properties (a) and (b) it follows by a mere re-

*This is not intended to exclude the case in which $R_i - 1 = 0$, in which the set of i circuits C_i^j is a null-set.

petition of the argument in § 48, Chap. II that R_i is an *Analysis Situs* invariant of the complex C_n .

43. It should perhaps be pointed out explicitly that the proof which has just been completed applies as well for $i = n$ as for other values of i . If C_n is a single n -circuit, $R_n = 2$, and since R_n is an invariant, any complex C'_n homeomorphic with C_n contains just one n -circuit. By a repetition of the argument in § 52, Chap. II, it follows that this n -circuit contains all points of C'_n . Hence any complex homeomorphic with an n -circuit is an n -circuit.

CHAPTER IV

ORIENTABLE MANIFOLDS

Oriented n -Cells

1. Let us now take up the orientation of n -dimensional complexes. The first problem is to give a definition of the term "oriented n -cell." We shall give a definition here which suffices for the elementary part of the matrix theory and shall postpone to the next chapter the theorems on deformation which give the full intuitional content of the notion of orientation. The definition will be made as a part of a process of mathematical induction in which we prove that if certain theorems are true and certain terms defined for all complexes C_i for which $i < n$, then the theorems are true and the terms can be defined for any complex C_n . Since the theorems and definitions in question have already been established for all linear graphs, C_1 , this process will establish them for all complexes C_n .

The terms which we assume to be defined are: oriented i -cell of a complex C_j ($i, j < n$) orientable i -circuit ($i < n$), oriented i -circuit ($i < n$), oriented i -dimensional complex ($i < n$), sum of oriented i -dimensional complexes ($i < n$). The theorems are: (1) any i -circuit ($i < n$) which is homeomorphic with an orientable i -circuit is orientable; (2) any i -circuit defining an i -dimensional sphere ($i < n$) is orientable.

2. The proof that these theorems hold for any C_n if they hold for all C_i ($i < n$) is a direct generalization of the proof given in §§ 58 to 60, Chap. II for the case $n = 2$, and will be given in § 10. Before establishing the theorems we state the definitions which, it will be noted, derive their content from the theorems for the cases $i < n$.

An oriented n -cell of a complex C_n is the object obtained by associating a cell a_i^n ($i = 1, 2, \dots, \alpha_n$) of C_n with one

$$(1) \quad \sigma_1^0, \sigma_1^1, \sigma_2^0, \sigma_2^1, \dots, \sigma_{\alpha_0}^0, \sigma_{\alpha_0}^1, \sigma_1^0,$$

in which each oriented cell is either positively or negatively related to the one which follows it. According to the convention that σ_i^0 is formed from σ_i^1 by associating it with $+1$, each σ_i^1 is negatively related to the oriented 0-cell which follows it if it is positively related to the one which precedes it, and *vice versa*. Hence by assigning the notation so that σ_j^1 is in every case positively related to the oriented 0-cell which precedes it in the sequence (1) we can arrange that $\sigma_1^1, \sigma_2^1, \dots, \sigma_{\alpha_1}^1$, represent a set of oriented 1-cells such that each oriented 0-cell positively related to one oriented 1-cell of the set is negatively related to another. Such an oriented complex formed from the 1-cells of a 1-circuit is called an *oriented 1-circuit*.

It is obvious that the only other oriented 1-circuit which can be formed from the given 1-circuit is that composed of $-\sigma_1^1, -\sigma_2^1, \dots, -\sigma_{\alpha_1}^1$. For if one of the oriented 1-cells in an oriented 1-circuit be replaced by its negative each of the other 1-cells must be replaced by its negative. The other oriented complexes which can be formed from the 1-circuit are not oriented 1-circuits.

Intuitively this discussion means that if the oriented 1-cells of an oriented 1-circuit are marked by arrows as in § 34, the arrows must all be pointed in the same direction.

Matrices of Orientation

36. The relations between the oriented 0-cells and oriented 1-cells, which can be formed from the cells of a complex C_1 may be studied by means of two matrices which are closely analogous to H_0 and H_1 . The new matrices will be called *matrices of orientation*, and denoted by E_0 and E_1 . In our treatment they are derived from H_0 and H_1 and their theory is entirely parallel to that of H_0 and H_1 . They are, however, the one- and two-dimensional instances of the matrices E_i which form the central element in Poincaré's work on Analysis

Situs. The matrix E_1 may be said to date back to the article by G. Kirchoff in Poggendorf's *Annalen der Physik*, Vol. 72 (1847), p. 497, on the flow of electricity through a network of wires, in which Kirchoff made use of a system of linear equations having E_1 as its matrix. This paper is doubtless the first important contribution to the theory of linear graphs.

37. Any set of oriented 0-cells may be denoted by a symbol $(x_1, x_2, \dots, x_{\alpha_0})$ in which x_i is $+1$ if σ_i^0 is in the set, -1 if $-\sigma_i^0$ is in the set, and 0 if neither σ_i^0 nor $-\sigma_i^0$ is in the set. The symbols for the bounding oriented 0-circuits of a complex C_1 satisfy a set of equations, (E_0) , identical with the equations (H_0) of § 19 except that the variables are taken to be integers instead of being reduced modulo 2. The corresponding matrix will be denoted by

$$E_0 = \|\|\epsilon_{ij}^0\|\| \quad (i = 1, 2, \dots, R_0; j = 1, 2, \dots, \alpha_0).$$

If the complex is connected, $R_0 = 1$ and this matrix reduces to a one-rowed matrix

$$\|\|1, 1, \dots, 1\|\|$$

all of whose α_0 elements are unity. The equations (E_0) have $\alpha_0 - R_0$ linearly independent solutions, and if r_0 is the rank of E_0

$$r_0 = \rho_0 = R_0.$$

38. The relations between the oriented 0-cells σ_i^0 and oriented 1-cells σ_j^1 of an oriented complex C_1 may be denoted by a matrix

$$E_1 = \|\|\epsilon_{ij}^1\|\| \quad (i = 1, 2, \dots, \alpha_0; j = 1, 2, \dots, \alpha_1)$$

in which ϵ_{ij}^1 is $+1$ if σ_i^0 is positively related to σ_j^1 , is -1 if σ_i^0 is negatively related to σ_j^1 , and is 0 if σ_i^0 is not an end of σ_j^1 .

This matrix can be formed from H_1 by changing a 1 in each column to -1 , for each σ_i^1 is positively related to one of the σ^0 's formed from the ends of σ_i^1 and negatively related to the other. The choice of the -1 is determined by the arbitrary choice in the definition of σ_i^1 .