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2000 *Mathematics Subject Classification.* Primary 57Q45;
Secondary 20F36, 57M05, 57M12, 57M25, 57Q35.

ABSTRACT. Braid theory and knot theory are related to each other via two famous results due to Alexander and Markov. Alexander's theorem states that any knot or link can be put into braid form. Markov's theorem gives necessary and sufficient conditions to conclude that two braids represent the same knot or link. Thus one can use braid theory to study knot theory, and vice versa. In this book we generalize braid theory to dimension four. We develop the theory of surface braids and apply it to study surface links. Especially, the generalized Alexander and Markov theorems in dimension four are given. This book is the first place that contains a complete proof of the generalized Markov theorem.

Surface links are also studied via the motion picture method, and some important techniques of this method are studied. For surface braids, various methods to describe them are introduced and developed: the motion picture method, the chart description, the braid monodromy, and the braid system. These tools are fundamental to understanding and computing invariants of surface braids and surface links.

A table of knotted surfaces is included with a computation of Alexander polynomials. The braid techniques are extended to represent link homotopy classes.

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Contents

Preface

Knot theory is currently one of the most active research fields in topology. In the classical sense it is the study of circles (closed 1-manifold) in Euclidean 3-space or a 3-sphere S^3. This is generalized to higher dimensional knot theory and furthermore to the study of manifold pairs or topological space pairs up to homeomorphism (in the topological, PL, or smooth category). Since topology is the study of topological spaces up to homeomorphism, knot theory in this global sense is a quite wide area of topology. Two-dimensional knot theory or knot theory in dimension four deals with surfaces in 4-space. We will refer to them as "surface links" in this book. This is one branch of knot theory in the global sense. However it is very mysterious. Classical knots have been studied for a long time. Since they are objects in 3-space, one can watch them directly and handle them without difficulty. One can apply 3-manifold theory, which has also been studied for a long time, to knot theory and vice versa. Of course this does not mean that classical knot theory is easy. Since surface links are objects in 4-space, we cannot see and handle them directly. One method to compute with surface links is to use motion pictures which were introduced in 1962 in Fox's famous article "A quick trip through knot theory" [**168**]. Another method is to use projection images in 3-space called surface link diagrams. This method is quite convenient when we describe a local configuration of a surface link or try to generalize some notion in classical knot theory to 2-dimensional knot theory, because a lot of important notions for classical knots are defined or interpreted by use of classical knot diagrams. In this book we will mainly discuss motion pictures. One reason is that there is already a good book on surface link diagrams by Carter and Saito [**89**]. Another reason is that there are important techniques in the motion picture method that are not so familiar. One of the main goals of this book is to introduce 2-dimensional knot theory and the technique of the motion picture method.

Braid theory also has been studied for a long time. Pioneering and systematic studies of braids were introduced in Artin's "Theorie der Zopfe" [**15**] in 1925 and "Theory of braids" [**17**] in 1947. Braid theory and knot theory are related by two famous results due to Alexander [**5**] in 1923 and Markov [**567**] in 1935. Alexander's theorem states that any knot or link can be presented as a closed braid and Markov's theorem states that such a braid form is uniquely determined up to "braid isotopy", "conjugation" and "stabilization". Therefore one can use braid theory to study knot theory and vice versa. Birman's book "Braids, links, and mapping class groups" [**42**] in 1974 contains a lot of results that relate knots and braids. This book is also famous for a proof of Markov's theorem. A remarkable application of braids in knot theory is the polynomial invariant discovered by Jones [**298, 299**] in 1985. This is one of the most powerful tools in knot theory.

There are various generalizations of classical braids: Brieskorn and Saito [**62**] generalized Artin's braid group from a group theoretical point of view. Another generalization is the fundamental group of a certain space. For such a space, Dahm [**124**] and Goldsmith [**201, 202**] considered a space of n-links, and Manin and Schechtman [**566**] a space of hyperplane arrangements. Another generalization is a braided surface defined by Rudolph [**778, 783**]. This gave a lot of interesting applications to knot theory; especially, Seifert ribbons for closed braids, ribbon surfaces in the 4-disk and quasi-positive braids [**778, 779, 781, 782, 783, 790, 791, 792**]. Viro [**928**] (cf. [**316**]) introduced the notion of a 2-dimensional braid and established generalized Alexander theorem in dimension four: Any surface link can be described in a braid form (Theorem 23.6). In this book, 2-dimensional braids are referred to as surface braids. They are similar to the braided surfaces of Rudolph. In fact they are regarded as braided surfaces with trivial boundary. As an application, a characterization of 2-knot groups and surface link groups is obtained [**316**]. González-Acuña [**206**] defined another braid form for surface links and gave another characterization of surface link groups. In this book, we study surface braids.

This book is divided into five parts. **I.** The first part is introductory material in classical braid and knot theory. This part covers the material necessary for later use. One can read this part easily. **II.** The second part is an introduction to 2-dimensional knot theory (knot theory in dimension four). It is written mainly from the view point of the motion picture method. The first two parts are written at an elementary level and are almost self-contained so that beginners and undergraduates can easily read and understand. (Some parts of the second part are technical. The reader who has difficulty may skip through such parts.) **III.** The third part is the main introduction to surface braid theory (braid theory in dimension four). The goal of this part is to understand two important notions, "braid monodromy" and "chart description". These notions can be generalized and used not only for surface braids but also other materials related to braids. **IV.** The fourth part is devoted to establishing a relationship between surface braids and surface links. Generalized Alexander and Markov theorems are given in this part. The generalized Alexander theorem was proved by Viro [**928**] and the author [**316**]. The generalized Markov theorem was announced in [**317**]. This book is the first place that contains a complete proof of the generalized Markov theorem. The proof is based on a manuscript [**315**] and prepared here for specialists. The reader who wants to learn the basics is encouraged to skip over the proof part.) **V.** In the final part, surface links are studied from the view point of surface braid theory.

This book is written for a wide target audience from beginners (including graduates) to specialists. It can be used as a graduate textbook and also as a handbook for researchers.

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Seiichi Kamada

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