

# Cellular Cohomology in Homotopy Type Theory

Ulrik Buchholtz

Technische Universität Darmstadt

Darmstadt, Germany

buchholtz@mathematik.tu-darmstadt.de

Kuen-Bang Hou (Favonia)

Institute for Advanced Study

Princeton, NJ, USA

favonia@math.ias.edu

## ABSTRACT

We present a development of cellular cohomology in homotopy type theory. Cohomology associates to each space a sequence of abelian groups capturing part of its structure, and has the advantage over homotopy groups in that these abelian groups of many common spaces are easier to compute in many cases. Cellular cohomology is a special kind of cohomology designed for cell complexes; these are built in stages by attaching spheres of progressively higher dimension, and cellular cohomology defines the groups out of the combinatorial description of how spheres are attached. Our main result is that for finite cell complexes, a wide class of cohomology theories (including the ones defined through Eilenberg-MacLane spaces) can be calculated via cellular cohomology. This result was formalized in the Agda proof assistant.

## ACKNOWLEDGMENTS

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## 1 INTRODUCTION

*Homotopy type theory* (HoTT) [26] is a new area exploring the potential of type-theoretic presentations of homotopy theory, an area originating from the study of topological spaces up to continuous transformation. It facilitates computer checking of proofs, and in some case results in the discovery of new proofs. (See for example [21].) Many proofs have since been mechanized and checked by proof assistants such as Agda [8], Lean [15] and Coq [6]. HoTT sheds new light on how type theory can be understood and leads to new type theories based on the resulting insights [1–4, 12, 13].

One important concept in homotopy theory is homotopy groups, groups associated with every (pointed) space that reveals important structures of that space. However, it is difficult to calculate higher homotopy groups for many common spaces, for example spheres. As a result, homology and cohomology theories arise as an alternative way to study spaces.

The success of homotopy type theory begins with homotopy groups partially because of their simple type-theoretic definition. For example, the homotopy groups  $\pi_n(S^n)$  were calculated in [27].

Over time people have been extending the success in homotopy and cohomology theories as well. This paper is yet another milestone we have achieved.

The basic idea of *cohomology theory* is to study functions from cycles in a space. Functions from the cycles at a fixed dimension  $n$  form a group, which is called the  $n$ th cohomology group. There are several ways to define a theory of such groups, some combinatorial and some axiomatic; amazingly, the classical theory states that the two approaches are essentially equivalent. Our goal is to recreate such an equivalence in HoTT.

In this paper we focus on a particular class of types, *CW complexes*, which come with an explicit description of how the space is built by iterated attachment of disks. We will then introduce *cellular cohomology theory*, a combinatorial cohomology theory specifically defined for CW complexes. After that, we will define ordinary *Eilenberg–Steenrod cohomology theory*, an axiomatic framework for cohomology theory.

A large part of the text and Agda formulation presented in this paper already appeared in Hou (Favonia)’s PhD thesis [20]. However, one critical lemma, Lemma 7.3, was stated as a conjecture and the main theorem was only proved after the thesis. During the study, a critical component, *degree*, was radically changed to facilitate the proving. Moreover, no materials in this paper have been published in any peer-reviewed journal or conference proceedings.

## 2 NOTATION

We assume that readers are familiar with common type-theoretic expressions in [20, 26]. In particular, we work in Martin-Löf type theory augmented with Voevodsky’s *univalence axiom* and the *pushout* type constructor for homotopy pushouts. From these ingredients we can define the propositional [14] and the higher dimensional truncations [25]. Our constructions also work in the proposed cubical type theories [1–4, 12, 13].

We often use the word “space” as a synonym for “type” in order to facilitate the intuition of types as spaces. Pointed arrows are specially marked as  $X \rightarrowtail Y$  for its importance in calculating degrees (Section 5). A special instance of pushouts that will occur throughout this paper is the *homotopy cofiber* of a pointed map  $f : X \rightarrowtail Y$ . It is defined to be the following pushout:

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \downarrow & & \downarrow \text{cofib} \\ 1 & \xrightarrow{\text{cofib}} & \text{cofiber}(f) \end{array}$$

If the map  $f$  is understood, we write  $Y/X := \text{cofiber}(f)$ .

# Homotopy Type And Homology

**Hans J. Baues**



## **Homotopy Type And Homology:**

*Homotopy Type and Homology* Hans J. Baues, 1996 Research mathematicians in algebraic topology will be interested in this new attempt to classify homotopy types of simply connected CW complexes This book provides a modern treatment of a long established set of questions in algebraic topology The author is a leading figure in this important research area

Rational Homotopy Type Wen-tsün Wu, 2006-11-14 This comprehensive monograph provides a self contained treatment of the theory of I measure or Sullivan s rational homotopy theory from a constructive point of view It centers on the notion of calculability which is due to the author himself as are the measure theoretical and constructive points of view in rational homotopy The I measure is shown to differ from other homology and homotopy measures in that it is calculable with respect to most of the important geometric constructions encountered in algebraic topology This approach provides a new method of treatment and leads to various new results In particular an axiomatic system of I measure is formulated quite different in spirit from the usual Eilenberg Steenrod axiomatic system for homology and giving at the same time an algorithmic method of computation of the I measure in concrete cases The book will be of interest to researchers in rational homotopy theory and will provide them with new ideas and lines of research to develop further

**Homology Theory** P. J. Hilton, S. Wylie, 1967

This account of algebraic topology is complete in itself assuming no previous knowledge of the subject It is used as a textbook for students in the final year of an undergraduate course or on graduate courses and as a handbook for mathematicians in other branches who want some knowledge of the subject

**Collected Works of Witold Hurewicz** Witold Hurewicz, Krystyna Kuperberg, 1995 This book contains papers of the outstanding and versatile mathematician Witold Hurewicz Preceding the collection are introductory articles describing Hurewicz s contributions to Borel sets dimension theory and algebraic topology Hurewicz first studied set theory and dimension and his papers on this topic are especially clear and precise making them accessible to beginning mathematicians His work in algebraic topology is marked by five fundamental papers which provide an introduction to homotopy groups and the Hurewicz Theorem concerning the relation between homotopy and singular homology These papers are included here in their original form along with English translations Each paper in the collection is followed by a review from one of the major reviewing journals These reviews were written by eminent mathematicians and serve as excellent abstracts for the papers

Basic Algebraic Topology and its Applications Mahima Ranjan Adhikari, 2016-09-16 This book provides an accessible introduction to algebraic topology a field at the intersection of topology geometry and algebra together with its applications Moreover it covers several related topics that are in fact important in the overall scheme of algebraic topology Comprising eighteen chapters and two appendices the book integrates various concepts of algebraic topology supported by examples exercises applications and historical notes Primarily intended as a textbook the book offers a valuable resource for undergraduate postgraduate and advanced mathematics students alike Focusing more on the geometric than on algebraic aspects of the subject as well as its natural

development the book conveys the basic language of modern algebraic topology by exploring homotopy homology and cohomology theories and examines a variety of spaces spheres projective spaces classical groups and their quotient spaces function spaces polyhedra topological groups Lie groups and cell complexes etc The book studies a variety of maps which are continuous functions between spaces It also reveals the importance of algebraic topology in contemporary mathematics theoretical physics computer science chemistry economics and the biological and medical sciences and encourages students to engage in further study

**An Introduction To Differential Geometry And Topology In Mathematical Physics**

Wang Rong, Chen Yue, 1999-01-18 This book gives an outline of the developments of differential geometry and topology in the twentieth century especially those which will be closely related to new discoveries in theoretical physics

Simplicial Complexes of Graphs Jakob Jonsson, 2007-11-15 A graph complex is a finite family of graphs closed under deletion of edges Graph complexes show up naturally in many different areas of mathematics Identifying each graph with its edge set one may view a graph complex as a simplicial complex and hence interpret it as a geometric object This volume examines topological properties of graph complexes focusing on homotopy type and homology Many of the proofs are based on Robin Forman's discrete version of Morse theory

*A Basic Course in Algebraic Topology* William S. Massey, 2019-06-28 This textbook is intended for a course in algebraic topology at the beginning graduate level The main topics covered are the classification of compact 2 manifolds the fundamental group covering spaces singular homology theory and singular cohomology theory These topics are developed systematically avoiding all unnecessary definitions terminology and technical machinery The text consists of material from the first five chapters of the author's earlier book *Algebraic Topology an Introduction* GTM 56 together with almost all of his book *Singular Homology Theory* GTM 70 The material from the two earlier books has been substantially revised corrected and brought up to date

**An Introduction to Algebraic Topology** Joseph J.

Rotman, 2013-11-11 There is a canard that every textbook of algebraic topology either ends with the definition of the Klein bottle or is a personal communication to J H C Whitehead Of course this is false as a glance at the books of Hilton and Wylie Maunder Munkres and Schubert reveals Still the canard does reflect some truth Too often one finds too much generality and too little attention to details There are two types of obstacle for the student learning algebraic topology The first is the formidable array of new techniques e g most students know very little homological algebra the second obstacle is that the basic definitions have been so abstracted that their geometric or analytic origins have been obscured I have tried to overcome these barriers In the first instance new definitions are introduced only when needed e g homology with coefficients and cohomology are deferred until after the Eilenberg Steenrod axioms have been verified for the three homology theories we treat singular simplicial and cellular Moreover many exercises are given to help the reader assimilate material In the second instance important definitions are often accompanied by an informal discussion describing their origins e g winding numbers are discussed before computing  $\pi_1$  The Green's theorem occurs before defining homology and differential

forms appear before introducing cohomology We assume that the reader has had a first course in point set topology but we do discuss quotient spaces path connectedness and function spaces Handbook of Algebraic Topology I.M.

James,1995-07-18 Algebraic topology also known as homotopy theory is a flourishing branch of modern mathematics It is very much an international subject and this is reflected in the background of the 36 leading experts who have contributed to the Handbook Written for the reader who already has a grounding in the subject the volume consists of 27 expository surveys covering the most active areas of research They provide the researcher with an up to date overview of this exciting branch of mathematics

**The Mathematical Legacy of Richard P. Stanley** Patricia Hersh,Thomas Lam,Pavlo Pylyavskyy,Victor Reiner,2016-12-08 Richard Stanley's work in combinatorics revolutionized and reshaped the subject His lectures papers and books inspired a generation of researchers In this volume these researchers explain how Stanley's vision and insights influenced and guided their own perspectives on the subject As a valuable bonus this book contains a collection of Stanley's short comments on each of his papers This book may serve as an introduction to several different threads of ongoing research in combinatorics as well as giving historical perspective *Fixed Points and Economic Equilibria* Ken Urai,2010

*Wuthering Heights* *Differential Geometry For Physicists* Bo-yu Hou,Bo-yuan Hou,1997-10-31 This book is divided into fourteen chapters with 18 appendices as introduction to prerequisite topological and algebraic knowledge etc The first seven chapters focus on local analysis This part can be used as a fundamental textbook for graduate students of theoretical physics Chapters 8 10 discuss geometry on fibre bundles which facilitates further reference for researchers The last four chapters deal with the Atiyah Singer index theorem its generalization and its application quantum anomaly cohomology field theory and noncommutative geometry giving the reader a glimpse of the frontier of current research in theoretical physics

**Algebraic Topology** Edwin H. Spanier,2012-12-06 Intended for use both as a text and a reference this book is an exposition of the fundamental ideas of algebraic topology The first third of the book covers the fundamental group its definition and its application in the study of covering spaces The focus then turns to homology theory including cohomology cup products cohomology operations and topological manifolds The remaining third of the book is devoted to Homotopy theory covering basic facts about homotopy groups applications to obstruction theory and computations of homotopy groups of spheres In the later parts the main emphasis is on the application to geometry of the algebraic tools developed earlier

**The Homology of Hopf Spaces** R.M. Kane,1988-08 This exposition of the theory of finite Hopf spaces details the development of the subject over the last thirty years with the homology of such spaces as its main theme The three chief areas of study in the volume are The study of finite H spaces with torsion free integral homology The study of finite H spaces with homology torsion The construction of finite H spaces

**Algebraic Topology** C. R. F. Maunder,1996-01-01 Based on lectures to advanced undergraduate and first year graduate students this is a thorough sophisticated and modern treatment of elementary algebraic topology essentially from a homotopy theoretic viewpoint Author C R F Maunder provides examples

and exercises and notes and references at the end of each chapter trace the historical development of the subject

*Encyclopaedia of Mathematics* Michiel Hazewinkel, 2013-12-01 This ENCYCLOPAEDIA OF MATHEMATICS aims to be a reference work for all parts of mathematics. It is a translation with updates and editorial comments of the Soviet Mathematical Encyclopaedia published by Soviet Encyclopaedia Publishing House in five volumes in 1977-1985. The annotated translation consists of ten volumes including a special index volume. There are three kinds of articles in this ENCYCLOPAEDIA. First of all, there are survey-type articles dealing with the various main directions in mathematics where a rather fine subdivision has been used. The main requirement for these articles has been that they should give a reasonably complete up-to-date account of the current state of affairs in these areas and that they should be maximally accessible. On the whole, these articles should be understandable to mathematics students in their first specialization years, to graduates from other mathematical areas, and depending on the specific subject, to specialists in other domains of science, engineers, and teachers of mathematics. These articles treat their material at a fairly general level and aim to give an idea of the kind of problems, techniques, and concepts involved in the area in question. They also contain background and motivation rather than precise statements of precise theorems with detailed definitions and technical details on how to carry out proofs and constructions. The second kind of article, of medium length, contains more detailed concrete problems, results, and techniques.

**Singularities and Low Dimensional Topology** Javier Fernández de Bobadilla, Marco Marengon, András Némethi, András Stipsicz, 2024-10-09 The special semester Singularities and low dimensional topology in the Spring of 2023 at the Erdős Center Budapest brought together algebraic geometers and topologists to discuss and explore the strong connection between surface singularities and topological properties of three and four dimensional manifolds. The semester featured a Winter School with four lecture series and several focused weeks. This volume contains the notes of the lecture series of the Winter School and some of the lecture notes from the focused weeks. Topics covered in this collection range from algebraic geometry of complex curves, lattice homology of curve and surface singularities to novel results in smooth four dimensional topology and grid homology and to Seiberg-Witten homotopy theory and specification of knot invariants. Some of these topics are already well documented in the literature and the lectures aim to provide a new perspective and fresh connections. Other topics are rather new and have been covered only in research papers. We hope that this volume will be useful not only for advanced graduate students and early stage researchers but also for the more experienced geometers and topologists who want to be informed about the latest developments in the field. [Proceedings Of The International Congress Of Mathematicians 2018 \(Icm 2018\) \(In 4 Volumes\)](#) Boyan Sirakov, Paulo Ney De Souza, Marcelo Viana, 2019-02-27 The Proceedings of the ICM publishes the talks by invited speakers at the conference organized by the International Mathematical Union every 4 years. It covers several areas of Mathematics and it includes the Fields Medal and Nevanlinna, Gauss, and Leelavati Prizes and the Chern Medal laureates. **Functions on Manifolds: Algebraic and Topological**

**Aspects** Vladimir Vasil'evich Sharko, 1993 This monograph covers in a unified manner new results on smooth functions on manifolds A major topic is Morse and Bott functions with a minimal number of singularities on manifolds of dimension greater than five Sharko computes obstructions to deformation of one Morse function into another on a simply connected manifold In addition a method is developed for constructing minimal chain complexes and homotopical systems in the sense of Whitehead This leads to conditions under which Morse functions on non simply connected manifolds exist Sharko also describes new homotopical invariants of manifolds which are used to substantially improve the Morse inequalities The conditions guaranteeing the existence of minimal round Morse functions are discussed

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