

# Covering Codes for Insertions and Deletions

Andreas Lenz, Cyrus Rashtchian, Paul H. Siegel, and Eitan Yaakobi

**Abstract**—A covering code is a set of codewords with the property that the union of balls, suitably defined, around these codewords covers an entire space. Generally, the goal is to find the covering code with the minimum size codeword. While most prior work on covering codes has focused on the Hamming metric, we consider the problem of designing covering codes defined in terms of insertions and deletions. First, we provide new sphere-covering lower bounds on the minimum possible size of such codes. Then, we provide new existential upper bounds on the size of optimal covering codes for a single insertion or a single deletion that are tight up to a constant factor. Finally, we derive improved upper bounds for covering codes using  $R \geq 2$  insertions or deletions. We prove that codes exist with density that is only a factor  $O(\sqrt{R} \log R)$  larger than the lower bounds for all fixed  $R$ . In particular, our upper bounds have an optimal dependence on the word length, and we achieve asymptotic density matching the best known bounds for Hamming distance covering codes.

**Index Terms**—covering codes, insertions and deletions.

## I. INTRODUCTION

Covering codes are a core object of study in coding theory and discrete mathematics. They have found applications in diverse areas such as data compression [1], football pools [2], circuit complexity [3], lattice problems [4], and approximate nearest neighbor search [5]. Previous work has mostly studied covering codes with respect to substitutions (i.e., the Hamming distance). Recently, due to the large amount of textual and biological data, there has been a resurgence of interest in the Levenshtein distance and in channels with insertion and deletion errors (e.g., [6], [7], [8], [9], [10], [11], [12]). Despite this substantial progress, the Levenshtein distance remains poorly understood compared to other metrics on discrete spaces, and many fundamental questions remain open.

In this paper, we study covering codes for insertions and deletions. Loosely speaking, we aim to cover a space of words by the union of balls around a minimum number of codewords. Let  $\Sigma_q^n$  denote the set of length- $n$  words over a  $q$ -ary alphabet. For the case of insertions and deletions, a codeword  $c \in \Sigma_q^n$

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covers a word  $y$  at radius  $R$  if  $y$  can be obtained from  $c$  by inserting, or respectively deleting, exactly  $R$  symbols. This means that the covering problem for insertions deals with finding a small set of words of length  $n$  such that each word of length  $n+R$  is a supersequence of a codeword. Similarly, for the case of deletions, each word of length  $n-R$  must be a subsequence of some codeword. In both cases, the codewords are the centers of balls with radius  $R$  under the Levenshtein distance. Notice, however, that the codewords and the covered words reside in different spaces because they have different lengths. Hence, the covering problem for insertions and deletions is inherently asymmetric.

Although there is a rich literature on covering codes for the Hamming distance [1], as well as recent improvements for insertion/deletion error-correcting codes (e.g., [13], [14], [15], [16], [17]), much less is known about covering codes using insertions or deletions. Two key challenges are the (ir)regularity of the balls and the asymmetry of the covering problem. Insertion balls are regular, in the sense that for any  $a \in \Sigma_q^n$  and  $R \geq 1$ , there are exactly  $\sum_{i=0}^{n+R} \binom{n+R}{i} (q-1)^i$  words of length  $n+R$  obtainable by inserting  $R$  symbols into  $a$  (cf. [18]). In contrast, deletion balls are irregular, and their sizes depend on many properties of their center, such as the number of runs. In fact, a tractable exact formula remains unknown for the size of the deletion balls with radius three or greater. This irregularity and lack of an explicit formula for the ball size means that, compared to the Hamming distance, it is inherently more challenging to derive bounds on the minimum covering code size, even asymptotically.

In some cases, we can infer results on covering codes from the theory of error-correcting codes. This is due to the existence of *perfect* error-correcting codes, for which the balls of radius  $R$  around all codewords are not only distinct but also cover each word once. For example, the Varshamov-Tenengolts (VT) code is a perfect binary single-deletion-correcting code [19]. It is known that the VT code is the largest single-deletion-correcting code for  $n \leq 14$  [20], and this is conjectured to be true for  $n > 14$  (see Sloane [21, Conj. 2.6]). This conjecture however remains open. Nevertheless, since the VT code is indeed a perfect single-deletion-correcting code, it is also a single-deletion-covering code.

While it has been shown that an  $R$ -deletion-correcting code is equivalent to an  $R$ -insertion-and-deletion-correcting code [26], this property does not hold for the case of covering codes. This means that the VT codes are not single-insertion-covering codes and thus also not perfect codes for correcting a single insertion. In fact, it has been shown that the only perfect single-insertion-correcting codes are binary and have length two [19]. Therefore, the best possible size of a single-insertion-covering code is unknown, and constructing optimal covering codes in this case is a highly non-trivial problem,

# Covering Codes Covering Codes

**Marinus Struik**

## **Covering Codes**

*Covering Codes* G. Cohen,I. Honkala,S. Litsyn,A. Lobstein,1997-04-14 The problems of constructing covering codes and of estimating their parameters are the main concern of this book It provides a unified account of the most recent theory of covering codes and shows how a number of mathematical and engineering issues are related to covering problems Scientists involved in discrete mathematics combinatorics computer science information theory geometry algebra or number theory will find the book of particular significance It is designed both as an introductory textbook for the beginner and as a reference book for the expert mathematician and engineer A number of unsolved problems suitable for research projects are also discussed

*The Covering Excess Method in the Theory of Covering Codes* Wolfgang Haas,2008 **Constructing Covering Codes** Luca Teodoro Filippini,2016

**Classification Algorithms for Codes and Designs** Petteri Kaski,Patric

R.J. Östergård,2006-02-03 A new starting point and a new method are requisite to insure a complete classification of the Steiner triple systems of order 15 This method was furnished and its tedious and difficult execution und taken by Mr Cole F N Cole L D Cummings and H S White 1917 129 The history of classifying combinatorial objects is as old as the history of the objects themselves In the mid 19th century Kirkman Steiner and others became the fathers of modern combinatorics and their work on various objects including what became later known as Steiner triple systems led to several classification results Almost a century earlier in 1782 Euler 180 published some results on classifying small Latin squares but for the first few steps in this direction one should actually go at least as far back as ancient Greece and the proof that there are exactly five Platonic solids One of the most remarkable achievements in the early pre computer era is the classification of the Steiner triple systems of order 15 quoted above An onerous task that today no sensible person would attempt by hand calculation Because with the exception of occasional parameters for which combinatorial arguments are effective often to prove nonexistence or uniqueness classification in general is about algorithms and computation

*Covering Codes* Gérard Cohen,1997 The problems of constructing covering codes and of estimating their parameters are the main concern of this book It provides a unified account of the most recent theory of covering codes and shows how a number of mathematical and engineering issues are related to covering problems Scientists involved in discrete mathematics combinatorics computer science information theory geometry algebra or number theory will find the book of particular significance It is designed both as an introductory textbook for the beginner and as a reference book for the expert mathematician and engineer A number of unsolved problems suitable for research projects are also discussed

*Covering Codes* Uri Blass,2003 **Covering Codes, Perfect Codes, and Codes from Algebraic Curves** Gerardus Joannes Maria Van Wee,1991

*Applied Algebra, Algebraic Algorithms and Error-Correcting Codes* Gérard Cohen,Marc Giusti,Teo Mora,1995 This book constitutes the proceedings of the 11th International Conference on Applied Algebra Algebraic Algorithms and Error Correcting Codes AAECC 11 held in Paris France in July 1995 The volume presents five invited papers and 32 full revised research papers selected from a total of

68 submissions it is focussed on research directed to the exploitation of algebraic techniques and methodologies for the application in coding and computer algebra Among the topics covered are coding cryptoloy communication factorization of polynomials Gr bner bases computer algebra algebraic algorithms symbolic computation algebraic manipulation

**Construction methods for covering codes** Patric R. J. Östergård,1993 *Covering Codes* Marinus Struik,1994

Selected Areas in Cryptography Alex Biryukov,Guang Gong,Douglas R. Stinson,2011-03-03 This book constitutes the thoroughly refereed post proceedings of the 17th Annual International Workshop on Selected Areas in Cryptography SAC 2010 held in Waterloo Ontario Canada in August 2010 The 24 revised full papers presented together with 2 invited papers were carefully reviewed and selected from 90 submissions The papers are organized in topical sections on hash functions stream ciphers efficient implementations coding and combinatorics block ciphers side channel attacks and mathematical aspects *Scientific and Technical Aerospace Reports* ,1992-06

### **Fast Generation and Covering Radius of**

**Reed-Muller Codes** Argyrios Alexopoulos,2009 Reed Muller codes are known to be some of the oldest simplest and most elegant error correcting codes Reed Muller codes were invented in 1954 by D E Muller and I S Reed and were an important extension of the Hamming and Golay codes because they gave more flexibility in the size of the codeword and the number of errors that could be correct The covering radius of these codes as well as the fast construction of covering codes is the main subject of this thesis The covering radius problem is important because of the problem of constructing codes having a specified length and dimension Codes with a reasonably small covering radius are highly desired in digital communication environments In addition a new algorithm is presented that allows the use of a compact way to represent Reed Muller codes Using this algorithm a new method for fast less complex and memory efficient generation of 1st and 2nd order Reed Muller codes and their hardware implementation is possible It is also allows the fast construction of a new subcode class of 2nd order Reed Muller codes with good properties Finally by reversing this algorithm we introduce a code compression method and at the same time a fast efficient and promising error correction process

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**Acme Commodity and Phrase Code** Acme Code Company,1923 **Western Union Telegraphic Code** International Cable Directory Company,1901 *Covering Codes* René Struik,1994 **Maryland Digest Annotated, Covering All Reported and Many Unreported Decisions, from 1 Harris and McHenry to 123 Maryland... Under the American Digest Classification** Samuel Want,J. Mercer Garnett (Jr.),Daniel List Warner,1916

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