# Lecture Notes in Computer Science 

Edited by G. Goos and J. Hartmanis

101

## André Thayse

## Boolean Calculus of Differences



Springer-Verlag
Berlin Heidelberg New York 1981

## Editorial Board

W. Brauer • P. Brinch Hansen • D. Gries • C. Moler • G. Seegmüller J. Stoer • N. Wirth

## Author

André Thayse
Philips Research Laboratory
av. Van Becelaere, 2
B-1170 Brussels
Belgium

AMS Subject Classifications (1979): 94C05, 94C10 CR Subject Classifications (1979): 6.1

ISBN 3-540-10286-8 Springer-Verlag Berlin Heidelberg New York ISBN 0-387-10286-8 Springer-Verlag New York Heidelberg Berlin

## FOREWORD

by Sheldon B. Akers

The development of switching circuit theory over the past three decades has mirrored the varying concerns of the logic designers who have had to confront the many problems presented by constantly changing circuit technologies. All too often, yesterday's elegant solution has been rendered obsolete by today's technological breakthrough. It is not surprising, therefore, that the accepted techniques and procedures of present day switching circuit theory too often tend to stand as distinct entities rather than as part of a cohesive whole.

Accordingly, it is a great pleasure to be able to recommend a book which not only provides a much needed historical perspective to these many developments but, even more importantly, does so within the framework of a single comprehensive structure. Starting with the basic definitions of Boolean algebra and the Boolean difference, the author carefully and systematically develops and extends these concepts to subsume such diverse areas as two-level minimization, hazard detection, unate functions, fault diagnosis, functional decomposition, and many others. A significant part of this theory derives directly from previous work by the author and his colleagues at the Philips Research Laboratory.

The elegance of the underlying theory, together with its breadth of coverage and the clarity of the author's presentation, is destined to make this book a classic in its field.

## Contents.

Preface of Prof. Sheldon B. Akers

1. Introduction ..... 1
2. Canonical expansions of Boolean functions ..... 5
2.1. General Boolean notations ..... 5
2.1.1. Definitions and elementary properties ..... 5
2.1.2. Boolean algebra ..... 6
2.1.3. Boolean ring ..... 7
2.1.4. The two element Boolean algebra ; Boolean functions ..... 9
2.1.5. Well-formed Boolean expression ; well-formed Galoisian expression ..... 9
2.2. Partial expansions with respect to one variable ..... 10
2.2.1. Lagrange expansion and redundant expansion ..... 10
2.2.2. Hybrid expansions ..... 12
2.2.3. Galoisian expansions ..... 12
2.2.4. Matrix expression of the canonical expansions ..... 13
2.2.5. Equivalent forms for canonical expansions ..... 13
2.3. Complete expansions ..... 14
2.3.1. Lagrange expansions ..... 14
2.3.2. The extended state vector ..... 15
2.3.3. Redundant canonical expansions ..... 16
2.3.4. Prime implicants and prime implicates ..... 17
2.3.5. Galoisian expansions ..... 18
3. Differences of Boolean functions ..... 19
3.1. Simple differences ..... 19
3.1.1. Definitions ..... 19
3.1.2. Functional properties ..... 20
3.1.3. Relations between the differences ..... 21
3.1.4. Relations between the function and its differences ..... 22
3.1.5. Relations between differences for a fixed operation ..... 22
3.1.6. Table of differences ..... 23
3.1.7. Lattice of differences ..... 25
3.1.8. The Boolean difference $\Delta^{A} f / \Delta x:$ properties and bibliographical ..... 28
notes
3.1.9. The meet difference $\mathrm{p}^{A_{f} / \mathrm{px}}$ : properties and bibliographical notes ..... 29
3.1.10. The join difference $q^{A} f / q x:$ properties and bibliographical notes ..... 31
3.1.11. Properties of the envelopes ..... 32
3.1,12. Envelopes and Galoisian expansions ..... 33
3.1.13. The oriented differences : properties and bibliographical notes ..... 34
3.1.14. Example ..... 35
3.2. Multiple differences ..... 36
3.2.1. Definitions and functional properties ..... 36
3.2.2. Expansions and properties of the function $T^{A^{A}}{ }_{f} / \mathrm{Tx}_{0}$ ..... 38
3.2.3. The function $\delta$ ..... 39
3.2.4. Generalization of theorem 3.l.3. ..... 41
3.2.5. Generalization of theorem 3.1.4. ..... 42
3.2.6. Functional properties of the meet and join differences ..... 44
3.2.7. Properties of the function $\delta$ ..... 45
3.2.8. Applications in switching theory ..... 46
3.2.9. The Boolean differences and the Galoisian expansions ..... 48
3.2.10. The Boolean differences and the circuit optimization ..... 50
3.2.11. The sensitivities ..... 50
3.2.12. Theorem ..... 52
3.2.13. Meaning of the sensitivity function ..... 53
3.2.14. Meaning of the function $S f / \mathrm{Sx}_{0} \oplus \delta f / \delta \mathrm{x}_{0}$
3.2.15. Theorem ..... 56
3.2.16. Generalization of theorem 3.1.11. ..... 56
3.2.17. Generalization of theorem 3.1.12. ..... 57
3.2.18. Application of the concept of envelope in switching theory ..... 57
3.2.19. Continuation of the example 3.1.14. ..... 58
4. Application to switching theory ..... 62
4.1. Introduction ..... 62
4.2. Universal algorithms ..... 62
4.2.1. Algorithms grounded on the extended vector ..... 62
4.2.1.1. Formulas and theorems ..... 62
4.2.1.2. The algebra derived from the general law ..... 65
4.2.1.3. Continuation of the example 3.1.14. ..... 65
4.2.2. Algorithm grounded on the generalized consensus ..... 69
4.2.2.1. Introduction ..... 69
4.2.2.2. The generalized consensus with respect to the law $\uparrow$ ..... 73
4.2.2.3. Continuation of example 3.1.14. ..... 76
4.2.2.4. Obtention of the matrix $\psi^{(\uparrow)}(f)$ from a diagonal matrix ..... 78
4.3. Particular algorithms related to circuit analysis synthesis methods ..... 79
4.3.1. Synthesis of two-1evel circuits using AND- and OR-gates ..... 79
4.3.1.1. Problem statement ..... 79
4.3.1.2. Algorithm ..... 80
4.3.1.3. Theorem ..... 81
4.3.1.4. Algorithm ..... 82
4.3.1.5. Computation method for obtaining $p f / p \underline{x}^{k}$ and $q f / q \underline{x}^{k}$ ..... 82
4.3.1.6. Algorithm ..... 83
4.3.1.7. Example ..... 84
4.3.1.8. Algorithm grounded on the use of the extended vector ..... 93
4.3.2. Synthesis of three-level networks using AND- and OR-gates ..... 96
4.3.2.1. Problem statement ..... 96
4.3.2.2. Algorithm ..... 96
4.3.2.3. Some further considerations related to logical design ..... 97
4.3.3. Two-level networks using AND and EX-OR gates ..... 102
4.3.3.1. Problem statement ..... 102
4.3.3.2. Algorithms grounded on the use of differential operators ..... 103
4.3.3.3. Algorithms grounded on the use of the Taylor expansions ..... 105
4.3.3.4. Algorithm grounded on the Kronecker matrix product ..... 107
4.4. Analysis of combinatorial networks ..... 108
4.4.1. Problem statement ..... 108
4.4.2. Hazard detection ..... 108
4.4.2.1. Problem statement ..... 108
4.4.2.2. Algorithms ..... 110
4.4.2.3. Example ..... 111
4.4.3. Fault detection ..... 111
4.4.3.1. Problem statement ..... 111
4.4.3.2. Computation of test functions for simple faults ..... 114
4.4.3.3. Computation of test functions for multiple faults ..... 114
4.4.3.4. Algorithm and examples ..... 116
4.4.3.5. Continuation of example 4.2.1.7. ..... 120
4.5. Detection of functional properties ..... 120
4.5.1. Detection of the decomposition ..... 120
4.5.1.1. Problem statement ..... 120
4.5.1.2. Decomposition classification ..... 121
4.5.1.3. The results of Ashenurst and Curtis ..... 122
4.5.1.4. Fundamental theorems for simple decompositions ..... 123
4.5.1.5. Algorithm for disjunctive decomposition detection ..... 127
4.5.2. Detection of symmetry ..... 128
4.5.3. Detection of A-degeneracy ..... 129
4.5.4. Other applications ..... 130
References ..... 131
Author index ..... 140
Subject index ..... 142
List of symbols ..... 144
