On the equivalence covering number of splitgraphs

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On the equivalence covering number of splitgraphs

by

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94/39
On the equivalence covering number of splitgraphs

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Abstract

An equivalence graph is a disjoint union of cliques. For a graph $G$ let $eq(G)$ be the minimum number of equivalence subgraphs of $G$ needed to cover all edges of $G$. We call $eq(G)$ the equivalence covering number of $G$. We show that the equivalence covering number for splitgraphs can be approximated within an additive constant 1. We also show that obtaining the exact value of the equivalence number of a splitgraph is an NP-hard problem. Using a similar method we also show that the computation of the equivalence number remains NP-complete for graphs with maximum degree 6 and with maximum clique number 4.

1 Introduction

Definition 1 An equivalence graph is a vertex disjoint union of cliques. An equivalence covering of a graph $G$ is a family of equivalence subgraphs of $G$ such that every edge of $G$ is an edge of at least one member of the family. The equivalence covering number of $G$, denoted by $eq(G)$, is the minimum cardinality of all equivalence coverings of $G$.

The equivalence covering number was studied first in [2]. Interesting bounds for the equivalence covering number in terms of maximal degree of the complement were obtained in [1]. In this note we mainly consider the computation of the equivalence covering number of splitgraphs. We first show an approximation within an additive constant 1. Then we show that obtaining the exact value is an NP-hard problem.

Definition 2 A graph $G = (V, E)$ is a split graph, if there is a partition $V = S + K$ of its vertex set into a stable set $S$ and a clique $K$.

There is no restriction on edges between vertices of $S$ and vertices of $K$. Notice that in general the partition into $S$ and $K$ need not be unique. Splitgraphs are exactly those graphs which, together with their complements, are chordal. For more general information on splitgraphs we refer to [4].

2 Approximation

In this section we show that the equivalence covering number of a splitgraph can be approximated within an additive constant 1. Consider a partition $V = S + K$ of the vertex set into an independent set $S$ and a clique $K$. For a vertex $x$ in $K$ let $\delta(x)$ be the number of neighbors of $x$ in $S$. Let $\Delta = \max\{\delta(x) \mid x \in K\}$.

Lemma 1 $eq(G) \geq \Delta$. 
Proof. Consider a vertex \( x \in K \) with \( \delta(x) = \Delta \) and its neighbors in \( S \). This is a \( K_{1,\Delta} \) induced subgraph of \( G \). This induced subgraph has equivalence covering number \( \Delta \), since each equivalence graph in the covering can have only one edge. This proves the lemma.

\[ \text{Lemma 2 } eq(G) \leq \Delta + 1. \]

\[ \text{Proof. Let } y_1, \ldots, y_t \text{ be the vertices of } S. \text{ For each vertex } x \in K \text{ consider an arbitrary ordering of its neighbors in } S. \text{ For } i = 1, \ldots, \Delta \text{ define the equivalence graph } G_i \text{ as follows. } G_i \text{ is the disjoint union of cliques } W_{ij} = \{y_j\} \cup \{x \in K \mid \text{the } i\text{th neighbor of } x \text{ is } y_j\}, \text{ for } j = 1, \ldots, t. \text{ It is easy to check that the cliques } W_{ij} \text{ for } j = 1, \ldots, t \text{ are all disjoint. We define one more equivalence graph } G_{\Delta+1} \text{ consisting of the clique } K. \text{ Obviously, this gives an equivalence covering with } \Delta + 1 \text{ equivalence graphs.} \]

The approximation given in Lemma 2 can be computed in linear time. This proves the following theorem.

\[ \text{Theorem 1 There exists a linear time algorithm to compute an equivalence covering of a splitgraph } G \text{ with at most } eq(G) + 1 \text{ equivalence graphs.} \]

Remark 1 Notice that, in case the splitgraph is a threshold graph (see, e.g., [4]), its equivalence number can easily be computed exactly.

3 NP-completeness

We use a reduction from \textsc{edge-coloring}.

The \textit{chromatic index} of a graph \( G \), denoted by \( \chi'(G) \), is the number of colors required to color the edges of the graph in such a way that no two adjacent edges have the same color. By Vizing's theorem (see, e.g., [3]) the chromatic index is either \( d \) or \( d + 1 \), where \( d \) is the maximum vertex degree.

Notice that, in general, the chromatic index is an upperbound for the equivalence covering number. Also, these parameters coincide for triangle-free graphs. It follows that, for bipartite graphs, the equivalence covering number equals the maximum degree. Unfortunately, for splitgraphs the bound is not of much use, which is illustrated by a clique.

It is by now well-known that it is NP-complete to determine the chromatic index of an arbitrary graph [5, 6]. Holyer [5] obtained the following result.

\[ \text{Theorem 2 It is NP-complete to determine whether the chromatic index of a cubic graph is } 3 \text{ or } 4. \]

Consider a cubic graph \( G \) and construct a graph \( H \) as follows. For each edge \( e \) of \( G \) introduce a new vertex \( x_e \) and make this adjacent to the two endvertices of \( e \). We call \( x_e \) the special vertex at \( e \).

\[ \text{Lemma 3 } \chi'(G) = 3 \iff eq(H) = 3. \]

\[ \text{Proof. First assume } \chi'(G) = 3. \text{ Notice that } eq(H) \geq 3 \text{ since } H \text{ has an induced } K_{1,3} \text{ subgraph. (If } p \text{ is a vertex of } G \text{ incident with edges } e, f \text{ and } g \text{ in } G, \text{ then } \{p, x_e, x_f, x_g\} \text{ induces a } K_{1,3} \text{ in } H.) \text{ Consider an edge coloring of } G \text{ with three colors. For each color class define an equivalence graph as follows. For each edge in that color class, the triangle consisting of the edge and the special vertex at that edge is a clique of the equivalence graph. It is easy to check that this defines an equivalence covering with three equivalence graphs.}

Now assume \( H \) has an equivalence covering with three equivalence graphs \( H_1, H_2 \) and \( H_3 \). We claim that no triangle of \( G \) is contained in a clique of one of the equivalence graphs. Assume, by way of contradiction, that \{a, b, c\} is a triangle of \( G \) which is contained in a clique of \( H_1 \). Vertex \( a \) is adjacent to three special vertices, say \( x_1, x_2 \) and \( x_3 \). Then each of the edges \( (a, x_i) \) is contained in a clique of an equivalence graph, and no two are in a clique of the same equivalence graph. Without loss
of generality we may assume that \((a, x_i)\) is contained in a clique of \(H_i\). But then \(H_1\) cannot contain the triangle \(\{a, b, c\}\) since \(x_1\) has degree two and hence the clique containing \(a\) and \(x_1\) can have at most two vertices of \(G\).

We can color the edges of \(G\) as follows. If the edge \(e\) is contained in a clique of \(H_i\) then we give it color \(i\). (If \(e\) is contained in cliques of more than one equivalence graph, we can choose one arbitrarily). By the remark above this gives a correct edge-coloring with three colors.

\[\square\]

**Corollary 1** It is NP-complete to determine whether the equivalence covering number of a graph with maximum degree \(\leq 6\) and without induced \(K_4\) is 3 or 4.

Given a cubic graph \(G\) we construct a splitgraph \(G^*\) as follows. The vertex set of \(G^*\) is split into a clique \(K\) and an independent set \(S\). The vertices of \(K\) are the vertices of \(G\). For each edge \(e\) of \(G\) introduce two new vertices \(x_{e,1}\) and \(x_{e,2}\) which are both made adjacent to the endvertices of \(e\). For each nonedge \(f\) of \(G\), we introduce one new vertex \(y_f\) which is made adjacent to the endvertices of \(f\). We again call the new vertices, which are the vertices of \(S\), special vertices.

\[\text{Lemma 4} \quad 
\chi'(G) = 3 \Leftrightarrow \text{eq}(G^*) = n + 2, \quad \text{where} \ n \ \text{is the number of vertices of} \ G.\]

\[\text{Proof.} \quad \text{The proof goes along the same lines as the proof of Lemma 3. Assume} \ G \ \text{can be edge-colored with three colors. Notice that} \ \text{eq}(G^*) \geq n + 2 \ \text{since} \ K_{1,n+2} \ \text{is an induced subgraph. Since} \ G \ \text{is cubic,} \ n \ \text{is even. We can construct an equivalence covering for} \ G^* \ \text{as follows. First, consider an edge-coloring of} \ K \ \text{with} \ n - 1 \ \text{colors (see [3]). For each color class, define an equivalence graph as follows. For each edge in} \ K \ \text{in that color class, add one special vertex at that edge and let that triangle be a clique of the equivalence graph. Next consider an edge-coloring of} \ G \ \text{with three colors. For each color class define an equivalence graph as follows. For each edge in that color class add the other special vertex and let that triangle be a clique of the equivalence graph. Clearly, this defines an equivalence covering of} \ G^* \ \text{with} \ n + 2 \ \text{equivalence graphs. Assume that} \ G^* \ \text{has an equivalence covering with} \ n + 2 \ \text{equivalence graphs. Consider a vertex} \ a \in K. \ This \ vertex \ a \ \text{is adjacent to} \ n + 2 \ \text{special vertices, and each of the edges between} \ a \ \text{and a special vertex defines a unique equivalence graph. It follows that no triangle of} \ G \ \text{can be contained in a clique of an equivalence graph. We thus obtain a correct edge-coloring of} \ G \ \text{in the same manner as in the proof of Lemma 3.} \quad \square\]

\[\text{Corollary 2} \quad \text{It is NP-complete to determine whether the equivalence covering number of a splitgraph, in which every vertex of the independent set has degree two, is} \ \Delta \ \text{or} \ \Delta + 1, \ \text{where} \ \Delta = \max\{\delta(x) \mid x \in K\} \ \text{for a given partition of the vertex set into a clique} \ K \ \text{and an independent set} \ S.\]

\[\text{4 Concluding remarks}\]

In this note we considered the equivalence covering number for splitgraphs. Related problems are the clique covering number, and the clique partition number. The clique covering number is the minimum number of cliques which cover all the edges of the graph. It was shown in [8] that the clique covering number can be computed in linear time for chordal graphs. The clique partition number is the minimum number of cliques such that every edge is contained in exactly one clique. Determining the clique partition number is NP-hard for chordal graphs [9]. It would be interesting to determine the complexity of the computation of the clique partition number for split graphs. It should be remarked however that it is unlikely that a polynomial time algorithm exists, due to the following [10, 7]. Consider the following splitgraph \(G\). Take a
clique with \( m^2 + m + 1 - r \) vertices and an independent set with \( r \) vertices. Make every vertex of the independent set adjacent to every vertex of the clique. \((G\) is sometimes denoted as \( K_{m^2 + m + 1} \setminus K_r \).\) If \( 2 < r < m^2 + m + 1 \) then the clique partition number of \( G \) is at least \( m^2 + m \) with equality holding if and only if a projective plane of order \( m \) exists and \( r = m + 1 \).

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### Computing Science Reports

**Department of Mathematics and Computing Science**  
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**In this series appeared:**

<table>
<thead>
<tr>
<th>Volume</th>
<th>Authors</th>
<th>Title &amp; Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>91/02</td>
<td>R.P. Nederpelt H.C.M. de Swart</td>
<td>Implication. A survey of the different logical analyses &quot;if...,then...&quot;, p. 26.</td>
</tr>
<tr>
<td>91/03</td>
<td>J.P. Katoen L.A.M. Schoenmakers</td>
<td>Parallel Programs for the Recognition of $P$-invariant Segments, p. 16.</td>
</tr>
<tr>
<td>91/05</td>
<td>D. de Reus</td>
<td>An Implementation Model for GOOD, p. 18.</td>
</tr>
<tr>
<td>91/06</td>
<td>K.M. van Hee</td>
<td>SPECIFICATIEMETHODEN, een overzicht, p. 20.</td>
</tr>
<tr>
<td>91/07</td>
<td>E. Poll</td>
<td>CPO-models for second order lambda calculus with recursive types and subtyping, p. 49.</td>
</tr>
<tr>
<td>91/11</td>
<td>R.C. Backhouse P.J. de Bruin G. Malcolm E. Voermans J. van der Woude</td>
<td>Relational Catamorphism, p. 31.</td>
</tr>
<tr>
<td>91/12</td>
<td>E. van der Sluis</td>
<td>A parallel local search algorithm for the travelling salesman problem, p. 12.</td>
</tr>
<tr>
<td>91/14</td>
<td>P. Lemmens</td>
<td>The PDB Hypermedia Package. Why and how it was built, p. 63.</td>
</tr>
<tr>
<td>91/16</td>
<td>A.J.J.M. Marcelis</td>
<td>An example of proving attribute grammars correct: the representation of arithmetical expressions by DAGs, p. 25.</td>
</tr>
<tr>
<td>Paper Number</td>
<td>Authors</td>
<td>Title</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>91/18</td>
<td>Rik van Geldrop</td>
<td>Transformational Query Solving, p. 35.</td>
</tr>
<tr>
<td>91/19</td>
<td>Erik Poll</td>
<td>Some categorical properties for a model for second order lambda calculus with subtyping, p. 21.</td>
</tr>
<tr>
<td>91/23</td>
<td>K.M. van Hee, L.J. Somers, M. Voorhoeve</td>
<td>Z and high level Petri nets, p. 16.</td>
</tr>
<tr>
<td>91/24</td>
<td>A.T.M. Aerts, D. de Reus</td>
<td>Formal semantics for BRM with examples, p. 25.</td>
</tr>
<tr>
<td>91/25</td>
<td>P. Zhou, J. Hooman, R. Kuiper</td>
<td>A compositional proof system for real-time systems based on explicit clock temporal logic: soundness and completeness, p. 52.</td>
</tr>
<tr>
<td>91/27</td>
<td>F. de Boer, C. Palamidessi</td>
<td>Embedding as a tool for language comparison: On the CSP hierarchy, p. 17.</td>
</tr>
<tr>
<td>91/28</td>
<td>F. de Boer</td>
<td>A compositional proof system for dynamic process creation, p. 24.</td>
</tr>
<tr>
<td>91/30</td>
<td>J.C.M. Baeten, F.W. Vaandrager</td>
<td>An Algebra for Process Creation, p. 29.</td>
</tr>
<tr>
<td>91/31</td>
<td>H. ten Eikelder</td>
<td>Some algorithms to decide the equivalence of recursive types, p. 26.</td>
</tr>
<tr>
<td>91/33</td>
<td>W. v.d. Aalst</td>
<td>The modelling and analysis of queueing systems with QNM-ExSpect, p. 23.</td>
</tr>
<tr>
<td>91/34</td>
<td>J. Coenen</td>
<td>Specifying fault tolerant programs in deontic logic, p. 15.</td>
</tr>
<tr>
<td>Year</td>
<td>Authors</td>
<td>Title</td>
</tr>
<tr>
<td>------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>92/01</td>
<td>J. Coenen, J. Zwiers, W.-P. de Roever</td>
<td>A note on compositional refinement, p. 27.</td>
</tr>
<tr>
<td>92/02</td>
<td>J. Coenen, J. Hooman</td>
<td>A compositional semantics for fault tolerant real-time systems, p. 18.</td>
</tr>
<tr>
<td>92/03</td>
<td>J.C.M. Baeten, J.A. Bergstra</td>
<td>Real space process algebra, p. 42.</td>
</tr>
<tr>
<td>92/05</td>
<td>J.P.H.W.v.d.Eijnde</td>
<td>Conservative fixpoint functions on a graph, p. 25.</td>
</tr>
<tr>
<td>92/06</td>
<td>J.C.M. Baeten, J.A. Bergstra</td>
<td>Discrete time process algebra, p. 45.</td>
</tr>
<tr>
<td>92/07</td>
<td>R.P. Nederpelt</td>
<td>The fine-structure of lambda calculus, p. 110.</td>
</tr>
<tr>
<td>92/10</td>
<td>P.M.P. Rambags</td>
<td>Composition and decomposition in a CPN model, p. 55.</td>
</tr>
<tr>
<td>92/13</td>
<td>F. Kamareddine</td>
<td>Set theory and nominalisation, Part II, p. 22.</td>
</tr>
<tr>
<td>92/14</td>
<td>J.C.M. Baeten</td>
<td>The total order assumption, p. 10.</td>
</tr>
<tr>
<td>92/15</td>
<td>F. Kamareddine</td>
<td>A system at the cross-roads of functional and logic programming, p. 36.</td>
</tr>
<tr>
<td>92/16</td>
<td>R.R. Seljée</td>
<td>Integrity checking in deductive databases; an exposition, p. 32.</td>
</tr>
<tr>
<td>92/17</td>
<td>W.M.P. van der Aalst</td>
<td>Interval timed coloured Petri nets and their analysis, p. 20.</td>
</tr>
<tr>
<td>92/18</td>
<td>R.Nederpelt, F. Kamareddine</td>
<td>A unified approach to Type Theory through a refined lambda-calculus, p. 30.</td>
</tr>
<tr>
<td>92/20</td>
<td>F. Kamareddine</td>
<td>Are Types for Natural Language? P. 32.</td>
</tr>
<tr>
<td>Publication Number</td>
<td>Authors</td>
<td>Title</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>92/21</td>
<td>F.Kamareddine</td>
<td>Non well-foundedness and type freeness can unify the interpretation of functional application, p. 16.</td>
</tr>
<tr>
<td>92/22</td>
<td>R. Nederpelt, F.Kamareddine</td>
<td>A useful lambda notation, p. 17.</td>
</tr>
<tr>
<td>92/23</td>
<td>F.Kamareddine, E.Klein</td>
<td>Nominalization, Predication and Type Containment, p. 40.</td>
</tr>
<tr>
<td>92/24</td>
<td>M.Codish, D.Dams, Eyal Yardeni</td>
<td>Bottom-up Abstract Interpretation of Logic Programs, p. 33.</td>
</tr>
<tr>
<td>92/25</td>
<td>E.Poll</td>
<td>A Programming Logic for Fro, p. 15.</td>
</tr>
<tr>
<td>93/01</td>
<td>R. van Geldrop</td>
<td>Deriving the Aho-Corasick algorithms: a case study into the synergy of programming methods, p. 36.</td>
</tr>
<tr>
<td>93/02</td>
<td>T. Verhoeff</td>
<td>A continuous version of the Prisoner's Dilemma, p. 17</td>
</tr>
<tr>
<td>93/03</td>
<td>T. Verhoeff</td>
<td>Quicksort for linked lists, p. 8.</td>
</tr>
<tr>
<td>93/04</td>
<td>E.H.L. Aarts, J.H.M. Korst, P.J. Zwietering</td>
<td>Deterministic and randomized local search, p. 78.</td>
</tr>
<tr>
<td>93/05</td>
<td>J.C.M. Baeten, C. Verhoef</td>
<td>A congruence theorem for structured operational semantics with predicates, p. 18.</td>
</tr>
<tr>
<td>93/06</td>
<td>J.P. Veltkamp</td>
<td>On the unavoidability of metastable behaviour, p. 29</td>
</tr>
<tr>
<td>93/07</td>
<td>P.D. Moerland</td>
<td>Exercises in Multiprogramming, p. 97</td>
</tr>
<tr>
<td>93/08</td>
<td>J. Verhoosel</td>
<td>A Formal Deterministic Scheduling Model for Hard Real-Time Executions in DEDOS, p. 32.</td>
</tr>
<tr>
<td>93/10</td>
<td>K.M. van Hee</td>
<td>Systems Engineering: a Formal Approach Part II: Frameworks, p. 44.</td>
</tr>
<tr>
<td>93/13</td>
<td>K.M. van Hee</td>
<td>Systems Engineering: a Formal Approach</td>
</tr>
<tr>
<td>No.</td>
<td>Authors</td>
<td>Title</td>
</tr>
<tr>
<td>-----</td>
<td>----------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>93/16</td>
<td>H. Schepers and J. Hooman</td>
<td>A Trace-Based Compositional Proof Theory for Fault Tolerant Distributed Systems, p. 27.</td>
</tr>
<tr>
<td>93/17</td>
<td>D. Alstein and P. van der Stok</td>
<td>Hard Real-Time Reliable Multicast in the DEDOS system, p. 19.</td>
</tr>
<tr>
<td>93/18</td>
<td>C. Verhoef</td>
<td>A congruence theorem for structured operational semantics with predicates and negative premises, p. 22.</td>
</tr>
<tr>
<td>93/19</td>
<td>G.J. Houben</td>
<td>The Design of an Online Help Facility for ExSpect, p.21.</td>
</tr>
<tr>
<td>93/22</td>
<td>E. Poll</td>
<td>A Typechecker for Bijective Pure Type Systems, p. 28.</td>
</tr>
<tr>
<td>93/23</td>
<td>E. de Kogel</td>
<td>Relational Algebra and Equational Proofs, p. 23.</td>
</tr>
<tr>
<td>93/24</td>
<td>E. Poll and Paula Severi</td>
<td>Pure Type Systems with Definitions, p. 38.</td>
</tr>
<tr>
<td>93/26</td>
<td>W.M.P. van der Aalst</td>
<td>Multi-dimensional Petri nets, p. 25.</td>
</tr>
<tr>
<td>93/27</td>
<td>T. Kloks and D. Kratsch</td>
<td>Finding all minimal separators of a graph, p. 11.</td>
</tr>
<tr>
<td>93/28</td>
<td>F. Kamareddine and R. Nederpelt</td>
<td>A Semantics for a fine λ-calculus with de Bruijn indices, p. 49.</td>
</tr>
<tr>
<td>93/29</td>
<td>R. Post and P. De Bra</td>
<td>GOLD, a Graph Oriented Language for Databases, p. 42.</td>
</tr>
<tr>
<td>93/30</td>
<td>J. Deogun T. Kloks D. Kratsch H. Müller</td>
<td>On Vertex Ranking for Permutation and Other Graphs, p. 11.</td>
</tr>
<tr>
<td>93/31</td>
<td>W. Körver</td>
<td>Derivation of delay insensitive and speed independent CMOS circuits, using directed commands and production rule sets, p. 40.</td>
</tr>
</tbody>
</table>
93/33 L. Loyens and J. Moonen  
ILIAS, a sequential language for parallel matrix computations, p. 20.

93/34 J.C.M. Baeten and J.A. Bergstra  
Real Time Process Algebra with Infinitesimals, p.39.

93/35 W. Ferrer and P. Severi  
Abstract Reduction and Topology, p. 28.

93/36 J.C.M. Baeten and J.A. Bergstra  
Non Interleaving Process Algebra, p. 17.

93/37 J. Brunekeef  
Design and Analysis of Dynamic Leader Election Protocols in Broadcast Networks, p. 73.

93/38 C. Verhoef  
A general conservative extension theorem in process algebra, p. 17.

93/39 W.P.M. Nuijten  
Job Shop Scheduling by Constraint Satisfaction, p. 22.

93/39 E.H.L. Aarts  

93/39 D.A.A. van Erp Taalman Kip  

93/39 K.M. van Hee  

93/40 P.D.V. van der Stok  

93/40 M.M.M.P.J. Claessen  

93/40 D. Alstein  

93/41 A. Bijlsma  
Temporal operators viewed as predicate transformers, p. 11.

93/42 P.M.P. Rambags  
Automatic Verification of Regular Protocols in P/T Nets, p. 23.

93/43 B.W. Watson  
A taxonomy of finite automata construction algorithms, p. 87.

93/44 B.W. Watson  
A taxonomy of finite automata minimization algorithms, p. 23.

93/45 E.J. Luit  
A precise clock synchronization protocol, p.

93/45 J.M.M. Martin  

93/46 T. Kloks  

93/46 D. Kratsch  

93/46 J. Spinrad  

93/47 W. v.d. Aalst  

93/47 P. De Bra  

93/47 G.J. Houben  

93/47 Y. Kornatzky  

93/48 R. Gerth  
Verifying Sequentially Consistent Memory using Interface Refinement, p. 20.
94/01 P. America
M. van der Kammern
R.P. Nederpelt
O.S. van Roosmalen
H.C.M. de Swart

The object-oriented paradigm, p. 28.

94/02 F. Kamareddine
R.P. Nederpelt

Canonical typing and Π-conversion, p. 51.

94/03 L.B. Hartman
K.M. van Hee


94/04 J.C.M. Baeten
J.A. Bergstra

Graph isomorphism Models for Non Interleaving Process Algebra, p. 18.

94/05 P. Zhou
J. Hooman


94/06 T. Basten
T. Kunz
J. Black
M. Coffin
D. Taylor

Time and the Order of Abstract Events in Distributed Computations, p. 29.

94/07 K.R. Apt
R. Bol


94/08 O.S. van Roosmalen

A Hierarchical Diagrammatic Representation of Class Structure, p. 22.

94/09 J.C.M. Baeten
J.A. Bergstra

Process Algebra with Partial Choice, p. 16.

94/10 T. Verhoef

The testing Paradigm Applied to Network Structure, p. 31.

94/11 J. Peleska
C. Huizing
C. Petersohn


94/12 T. Kloks
D. Kratsch
H. Müller


94/13 R. Seljée

A New Method for Integrity Constraint checking in Deductive Databases, p. 34.

94/14 W. Peremans

Ups and Downs of Type Theory, p. 9.

94/15 R.J.M. Vaessens
E.H.L. Aarts
J.K. Lenstra

Job Shop Scheduling by Local Search, p. 21.

94/16 R.C. Backhouse
H. Doombos

Mathematical Induction Made Calculational, p. 36.

94/17 S. Mauw
M.A. Reniers

An Algebraic Semantics of Basic Message Sequence Charts, p. 9.
94/18 F. Kamareddine  
R. Nederpelt  
Refining Reduction in the Lambda Calculus, p. 15.

94/19 B.W. Watson  
The performance of single-keyword and multiple-keyword pattern matching algorithms, p. 46.

94/20 R. Bloo  
F. Kamareddine  
R. Nederpelt  
Beyond $\beta$-Reduction in Church's $\lambda \rightarrow$, p. 22.

94/21 B.W. Watson  
An introduction to the FIRE engine: A C++ toolkit for Finite automata and Regular Expressions.

94/22 B.W. Watson  
The design and implementation of the FIRE engine: A C++ toolkit for Finite automata and regular Expressions.

94/23 S. Mauw and M.A. Reniers  
An algebraic semantics of Message Sequence Charts, p. 43.

94/24 D. Dams  
O. Grumberg  
R. Gerth  
Abstract Interpretation of Reactive Systems: Abstractions Preserving $\forall$CTL*, $\exists$CTL* and CTL*, p. 28.

94/25 T. Kloks  
K_{1,5}-free and $W_4$-free graphs, p. 10.

94/26 R.R. Hoogerwoord  
On the foundations of functional programming: a programmer’s point of view, p. 54.

94/27 S. Mauw and H. Mulder  

94/28 C.W.A.M. van Overveld  
M. Verhoeven  

94/29 J. Hooman  
Correctness of Real Time Systems by Construction, p. 22.

94/30 J.C.M. Baeten  
J.A. Bergstra  
Gh. Stefanescu  
Process Algebra with Feedback, p. 22.

94/31 B.W. Watson  
R.E. Watson  
A Boyer-Moore type algorithm for regular expression pattern matching, p. 22.

94/32 J.J. Vereijken  

94/33 T. Laan  
A formalization of the Ramified Type Theory, p. 40.

94/34 R. Bloo  
F. Kamareddine  
R. Nederpelt  
The Barendregt Cube with Definitions and Generalised Reduction, p. 37.

94/35 J.C.M. Baeten  
S. Mauw  
Delayed choice: an operator for joining Message Sequence Charts, p. 15.

94/36 F. Kamareddine  
R. Nederpelt  
Canonical typing and $\Pi$-conversion in the Barendregt Cube, p. 19.
94/37 T. Basten
R. Bol
M. Voorhoeve

Simulating and Analyzing Railway Interlockings in
ExSpect, p. 30.

94/38 A. Bijlsma
C.S. Scholten

Point-free substitution, p. 10.