THE UNIVERSITY OF TULSA

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HOW TO PREPARE THE PERFECT

THESIS OR DISSERTATION DOCUMENT

by
Noah L. Schrick

A thesis submitted in partial fulfillment of

the requirements for the degree of Master of Science

in the Discipline of Computer Science

The Graduate School

The University of Tulsa

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A THESIS

APPROVED FOR THE DISCIPLINE OF

COMPUTER SCIENCE

By Thesis Committee

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ABSTRACT

Noah L. Schrick (Master of Science in Computer Science)

How to Prepare the Perfect Thesis or Dissertation Document

Directed by I. M. Brilliant

92 pp., Chapter 7: Conclusions and Future Works

<center>(29 words)</center>

In order to prepare a perfect thesis or dissertation, we do hereby follow these illustrious instructions to the letter.

ACKNOWLEDGEMENTS

I would like to thank everyone who has made this thesis template possible. Thanks and more thanks. In fact, let me give thanks all over the place.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 First Heading: The Introduction

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1.2 Second Heading

This is the text for the second section.

1.2.1 First Subheading

This is text for the first subsection.

1.2.2 Second Subheading

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First Sub-subsection Header: This language lies in the first sub subsection. Since they are the same font and indentation, the header looks a little bit like the text itself, so there is a colon and a little extra space after the sub-subsection heading. This is all taken care of in the TUthesis style page. Here, we refer to Appendix A and Appendix B to check that the references appear as capital letters.

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CHAPTER 2

RELATED WORKS

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CHAPTER 3

UTILITY EXTENSIONS TO THE RAGE ATTACK GRAPH GENERATOR

3.1   Path Walking

Due to the large-scale nature of Attack Graphs, analysis can prove difficult and time-consuming. With some networks reaching millions of states and edges, analyzing the entire network can be overwhelming complex. As a means of simplifying analysis, a potential strategy could be to consider only small subsets of the network at a time, rather than feeding the entire network into an analysis algorithm. To aid in this effort, a Path Walking feature was implemented as a separate program, and has two primary modes of usage. The goal of this feature is to provide a subset of the network that includes all possible paths from the root node to a designated node. The first mode is a manual mode, where a user can input the desired state to walk to, and the program will output a separate graph of all possible paths to the specified state. The second mode is an automatic mode, where the program will output seperate subgraphs to all states in the network that have qualities of "$compliance\_vio = true$" or "$compliance\_vios > 0$". This often produces multiple subgraphs, that can then be separately fed into an analysis program.

Figure 3.1 demonstates an output of the Path Walking feature when walking to state 14. In this figure, the primary observable feature is that the network was reduced from 16 states to 6 states, and 32 edges to 12 edges. The reduction from the original network to the subset varies on the overall connectivity of the original Attack Graph, but the reduction can aid in simplifying the analysis process if only certain states of the network are to be analyzed.

5
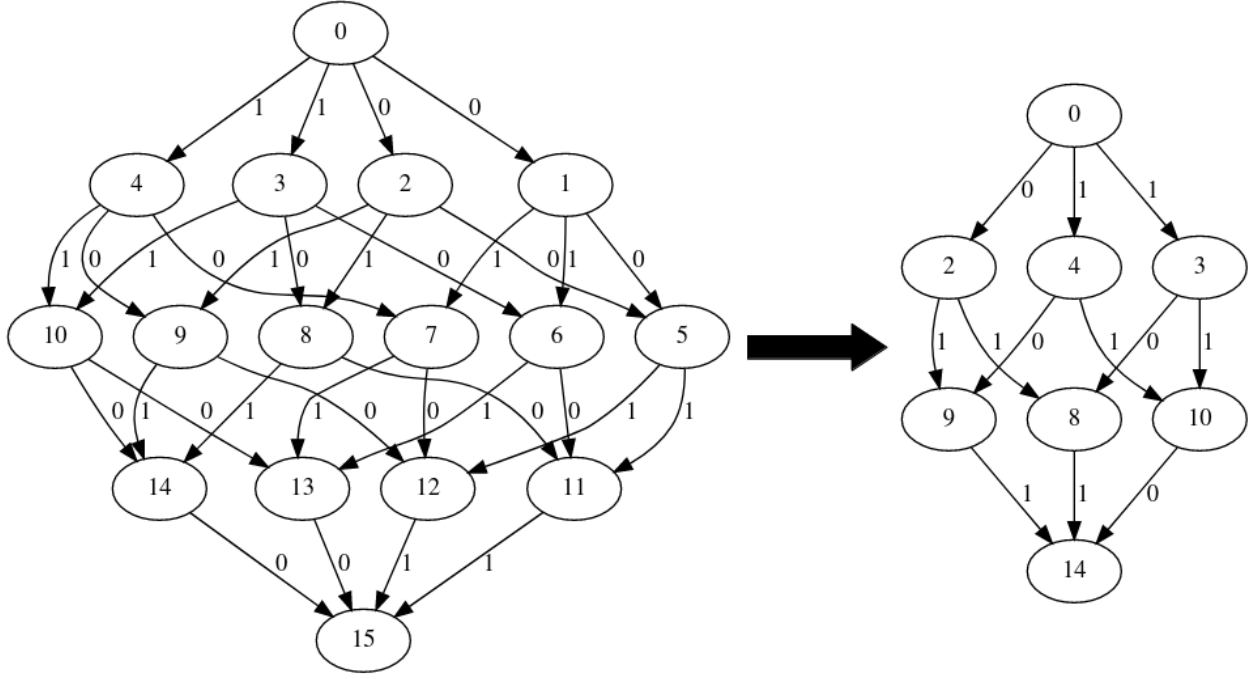
Figure 3.1: Path Walking to State 14

3.2 Compound Operators

Many of the networks previously generated by RAGE compromise of states with features that can be fully enumerated. In many of the generated networks, there is an established set of qualities that will be used, with an established set of values. These typically have included "$compliance\_vio = true/false$", "$root = true/false$", or other general "$true/false$" values or "$version = X$" qualities. To expand on the types and complexities of networks that can be generated, compound operators have been added to RAGE. When updating a state, rather than setting a quality to a specific value, the previous value can now be modified by an amount specified through standard compound operators such as $+=$, $-=$, $*=$, or $/=$.

The work conducted by the author of [1] when designing the software architecture included specifications for a quality encoding scheme. As the author discusses, qualities have four fields, which include the asset ID, attributes, operator, and value. The operator field is 4 bits, which allows for a total of 16 operators. Since the only operator in use at the

time was the " $=$ " operator, the addition of four compound operators does not surpass the 16 operator limit, and no encoding scheme changes were necessary. This also allows for additional compound operators to be incorporated in the future.

A few changes were necessary to allow for the addition of compound operators. Before the generation of an Attack Graph begins, all values are stored in a hash table. For previous networks generated by RAGE, this was not a difficulty, since all values could be fully enumerated and all possible values were known. When using compound operators however, not all values can be fully known. The concept of approximating which exploits will be applicable and what absolute minimum or maximum values will be prior to generation is a difficult task, so not all values can be enumerated and stored into the hash table. As a result, on-the-fly updates to the hash table needed to be added to the generator. The original key-value scheme for hash tables relied on utilizing the size of the hash table for values. Since the order in which updates happen may not always remain consistent (and is especially true in distributed computing environments), it is possible for states to receive different hash values with the original hashing scheme. To prevent this, the hashing scheme was adjusted so that the new value of the compound operator is inserted into the hash table values if it was not found, rather than the size of the hash table. Previously, there was no safety check for the hash table, so if the value was not found, the program would end execution. The assumption that this value can be inserted into the hash table is safe to make, since compound operators are conducted on numeric values, and matches the numeric type of the hash table.

3.3   Color Coding

As a visual aid for analysis purposes, color coding was another feature implemented as a postprocessing tool for RAGE. When viewing the output graph of RAGE, all states are originally identical in appearance, apart from number of edges, edge IDs, and state IDs. To allow for visual differentiation, color coding can be enabled in the run script. Color coding currently functions by working through the graph output text file, but it can be

extended to read directly from Postgres instead. The feature scans through the output file, and locates states that have *"compliance_vios = X"* (where X is a number greater than 0), or *"compliance_vio = true"*. For states that meet these properties, the color coding feature will add a color to the graphviz DOT file through the $[color = COL]$ attribute for the given node, where COL is assigned based on severity. For this version of color coding, severity is determined by the total number of compliance violations, but future versions can alter the severity measure through alternative means. Figure 3.2 displays an example graph that leverages color coding to easily identify problem states.
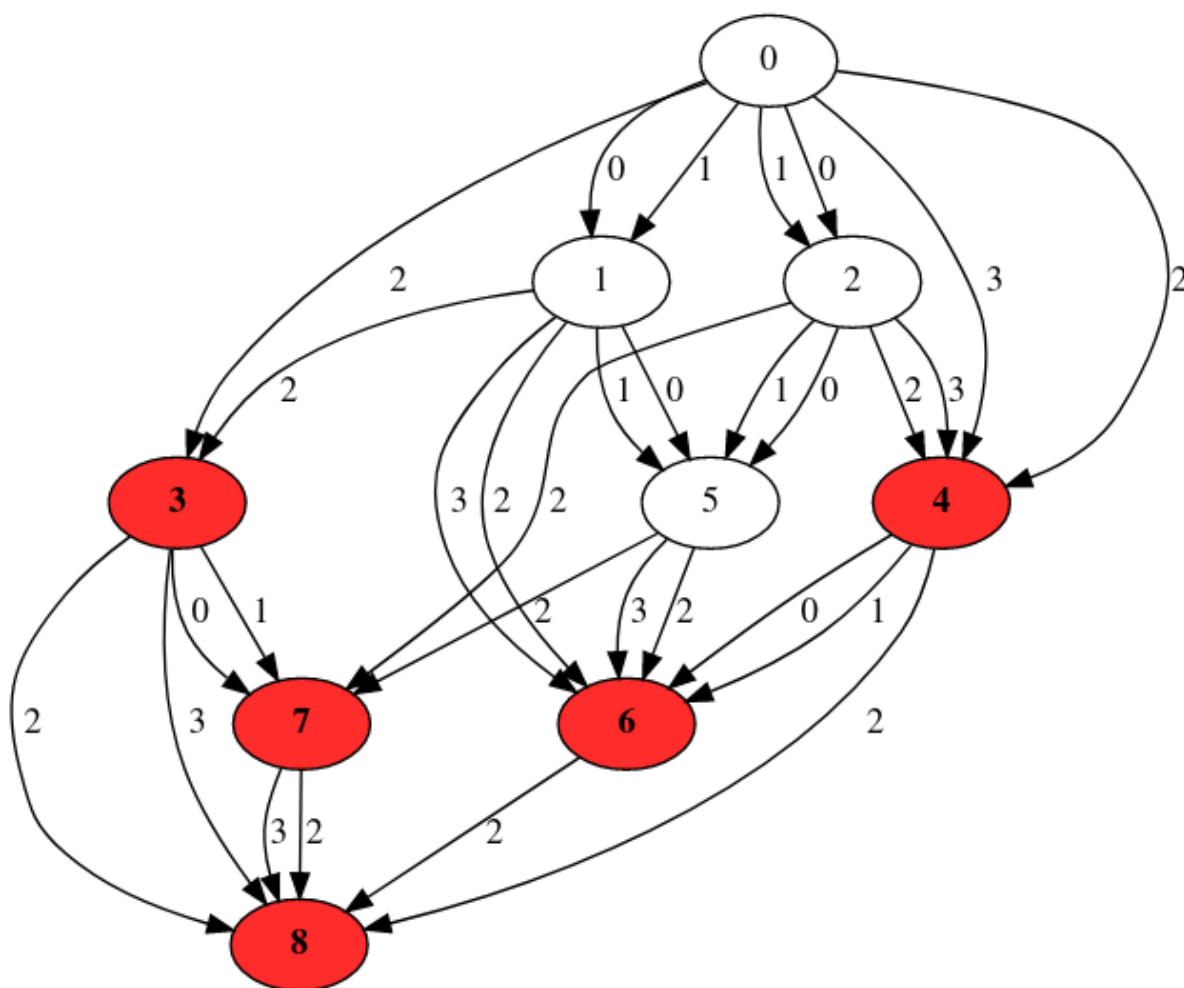

Figure 3.2: Color Coding a Small Network Based on Violations

3.4 Intermediate Database Storage

Previous works with RAGE have been designed around maximizing performance to limit the longer runtimes caused by the state space explosion, such as the works seen by the authors of [1], [3], and [2].

3.5 Relational Operators

Fifth section of the third chapter.

CHAPTER 4

SYNCHRONOUS FIRING

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CHAPTER 5

IMPLEMENTATION OF MESSAGE PASSING INTERFACE

5.1   Tasking Approach

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5.2   Subgraphing Approach

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CHAPTER 6

PERFORMANCE ANALYSIS

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CHAPTER 7

CONCLUSIONS AND FUTURE WORKS

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BIBLIOGRAPHY

[1] Kyle Cook. *RAGE: The Rage Attack Graph Engine*. PhD thesis, 2018.

[2] Ming Li, Peter Hawrylak, and John Hale. Combining OpenCL and MPI to support heterogeneous computing on a cluster. *ACM International Conference Proceeding Series*, 2019.

[3] Ming Li, Peter Hawrylak, and John Hale. Concurrency Strategies for Attack Graph Generation. *Proceedings - 2019 2nd International Conference on Data Intelligence and Security, ICDIS 2019*, pages 174–179, 2019.

APPENDIX A

THE FIRST APPENDIX

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APPENDIX B

THE SECOND APPENDIX

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B.1 A Heading in an Appendix

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B.1.1 A Subheading in an Appendix

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A Sub-subsection in an Appendix: And the sub subsection also works. Finally we test that figures and tables also work.

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