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FACULTY OF ENGINEERING

Electronics and Electrical Communication Engineering

Static Worst Case Execution Time Analysis for Pipelined Processor Architectures

A Thesis submitted in partial fulfilment of the requirements of the degree of

Doctor of Philosophy in Electrical Engineering

Electronics and Electrical Communication Engineering

by

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Statement

This thesis is submitted as a partial fulfilment of Doctor of Philosophy in Electrical Engineering, Faculty of Engineering, Ain shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

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Signature

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Date:

ABSTRACT

Worst Case Execution Time (WCET) estimation is substantial for scheduling analysis of real-time systems. Performing static WCET estimation requires performing program analysis as well as modeling the impact of complex micro-architectural features of modern processors such as; pipelining, instruction/data caching, dynamic branch prediction, out-of-order execution, speculative execution, and fine-grained chip multi-threading. The results of program analysis and of modeling can then be combined to obtain linear constraints which in turn can be solved by an Integer Linear Programming (ILP) solver. Automatically generating the integer linear equations that are used as input for the solvers remains a challenging task.

This thesis proposes a Domain Specific Language (DSL) called Constraint Generation Language (CGL) that can be used to describe the general constraints in a concise manner. The thesis also illustrates how CGL can be extended to automate the constraints generation from a program's branch flow graph and control flow graph. CGL's flexibility is demonstrated by using it with different ILP solvers.

Estimating the number of mispredictions is critically important for estimating the WCET for real-time systems. This thesis generalizes and improves over previous attempts to provide a safe and tight mispredication count estimate for various kinds of dynamic branch predictors. Finally, the thesis proposes an automatic method for calculating tight upper bounds on the number of loop iterations.

SUMMARY

A real-time system is a computer-based system in which the timing of the computed result and the actual value are of the same importance. One of the most common reasons for unexpected failures of the system is timing behavior. Worst Case Execution Time (WCET) estimation is substantial for scheduling analysis of real-time systems. Performing static WCET estimation requires performing program analysis as well as modeling the impact of complex micro-architectural features of modern processors such as; pipelining, instruction/data caching, dynamic branch prediction, out-of-order execution, speculative execution, and fine-grained chip multi-threading. The thesis proposes a set of tools and techniques to perform static WCET analysis for pipeline processor architectures.
This thesis is structured as follows:
Chapter 1 gives a general overview about the real-time systems and its types. The chapter discusses the need of the timing analysis for real-time systems. Finally, the motivation and the contributions of the thesis are described in this chapter.

Chapter 2 gives an overview of the WCET estimation techniques, features, and tools. Moreover, the previous works on WCET are reviewed in this chapter.

Chapter 3 overviews the necessary background on DSLs.

Chapter 4 proposes a domain specific language (DSL) called Constraint Generation Language (CGL) that can be used to describe the general constraints in a concise manner. In addition to the proposed language implementation, the syntax and semantics of CGL are formally given.

Chapter 5 presents the CGL's extension to automatically generate the linear constraints of WCET estimate for branch predictors. These linear constraints result from combining the program analysis with the impact model of complex micro-architectural features of modern processors; branch prediction. An ILP solver is used to solve these linear constraints to calculate the WCET estimate. CGL can be used with different ILP solvers as discussed in this chapter.

Chapter 6 introduces a novel approach that generalizes and improves over previous attempts to provide a safe and tight mispredication count estimate for dynamic branch predictors. The introduced approach gives closed formulas to compute mispredictions in

nested loops applicable to all variations of two-level adaptive branch predictors in addition to the gshare and gselect predictors. The given formulas are general enough to accommodate predictors with any counter size.

Chapter 7 presents an automatic method for calculating tight upper bound on the number of iterations for numerous loop structures including simple loops and nested ones whether they encapsulate conditions or not. A tight upper bound on the number of loop iterations contributes to obtain a safe and tight WCET estimate. The method is formalized by providing semantic rules for each supported loop structure.

Chapter 8 concludes the thesis commenting on the potential impact of the obtained results. In addition to a summary of the presented contributions, a discussion of future directions of research is presented.

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