

# Automatic compiler customization for novel hardware

**Automatische Anpassung von Compilern für neuartige Hardwarearchitekturen**

Master thesis by Janne Wulf

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## **Erklärung zur Abschlussarbeit gemäß §22 Abs. 7 und §23 Abs. 7 APB der TU Darmstadt**

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Hiermit versichere ich, Janne Wulf, die vorliegende Masterarbeit ohne Hilfe Dritter und nur mit den angegebenen Quellen und Hilfsmitteln angefertigt zu haben. Alle Stellen, die Quellen entnommen wurden, sind als solche kenntlich gemacht worden. Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

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Bei der abgegebenen Thesis stimmen die schriftliche und die zur Archivierung eingereichte elektronische Fassung gemäß §23 Abs. 7 APB überein.

Bei einer Thesis des Fachbereichs Architektur entspricht die eingereichte elektronische Fassung dem vorgestellten Modell und den vorgelegten Plänen.

Darmstadt, August 9, 2021

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J. Wulf

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# 1 Background

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In this chapter we are introducing knowledge which is required to understand the content of this thesis. In section 1.1 we give an overview about how a compiler is typically implemented and which problems it has to solve that we want to tackle. The sections 1.1.1 to 1.1.2 give a superficial overview of the first two phases of a typical compiler. Section 1.1.3 gives a more detailed introduction to compiler back ends, which we aim to optimize in this thesis.

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## 1.1 Compilers

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Making computer programs, that are written in high-level programming languages (e.g., C/C++, Java, Rust), executable on a specific machine is not a trivial task. Compilers are only one piece in the tool-chain required to make a program executable. The compiler translates the high-level language into assembly language, which is translated into object code by the assembler. Basic functionality like allocating memory or outputting strings on the screen is implemented in a standard library. The object code of the standard library and potentially other libraries are linked together with the translated program by the linker. There is more required to execute the code on a specific machine (e.g., a runtime library), but explaining this would go beyond the scope of this thesis.

The pure translation of the program is only one of the tasks a compiler has to fulfill. It also has to assure that the program is written in correct syntax of the high-level language. Most compilers will also optimize the given code and the translated code since a simple one-to-one translation would have a very poor performance. Eventually there has to be a mapping from variables and to the main memory and the processors registers. These are all by itself complex problems which are handled by a compiler.

Compilers are usually implemented in different phases to separate the different tasks and have a structured approach. A common approach to structure a compiler is by having a front end (section 1.1.1), an optional optimization (section 1.1.2) and a back end phase (section 1.1.3). These phases are explained in more detail in the following sub sections.

### 1.1.1 Front End

The front end phase is the first step in the translation process. Its implementation is dependent on the source language that has to be translated. A typical front end includes a scanner, a syntax checker/parser, a context-sensitive analysis and translation into a Intermediate Representation (IR). The scanner translates a stream of characters into a stream of tokens that are classified as parts of the source language. These tokens are then taken by the parser and are checked against the grammar defined by the source language. Even with a syntactically correct program, there can still be errors in the code, e.g., assignments of incompatible types.

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These are checked during the context-sensitive analysis phase. Eventually, the source code is translated into some kind of a IR which will be used as input to the optimizer and the back end.

There might be additional steps required depending on the source language. C/C++ compilers, for example, use a preprocessor to replace macros like **#include** and **#define** with their actual values.

### 1.1.2 Optimizer

### 1.1.3 Back End

#### Instruction Scheduling

Add Example: e.g. see <https://youtu.be/brpomKUynEA?t=271>

#### Register Allocation

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## 1.2 LLVM Compiler Infrastructure

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### 1.2.1 Intermediate Representation

### 1.2.2 Instruction Selection DAG



### 1.2.3 Pre-RA-Scheduling

Welche gibt es?  
Wie funktionieren sie?  
Welche Infos nutzen sie?

### 1.2.4 Post-RA-Scheduling

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## 1.3 Reinforcement Learning

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## 2 Related Work

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### 2.1 Instruction Scheduling

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**Code scheduling and register allocation in large basic blocks**

[goodman1988code]

**Learning Instruction Scheduling Heuristics from Optimal Data**

[russell2006learning]

**Learning to schedule straight-line code**

[moss1998learning]

**Using Genetic Algorithms to Fine-Tune Instruction-Scheduling Heuristics**

[beaty1996using]

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### 2.2 Register Allocation

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**Deep Learning-based Hybrid Graph-Coloring Algorithm for Register Allocation**

[das2019deep]

**Graph colouring meets deep learning: Effective graph neural network models for combinatorial problems**

[lemos2019graph]

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## Register Allocation for Intel Processor Graphics

[chen2018register]

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## 2.3 Compiler Phase-Ordering

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### Autophase: Compiler phase-ordering for hls with deep reinforcement learning

[huang2019autophase]

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## 2.4 Code Representation

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For making use of data driven techniques in the area of compiler optimization, it is required to somehow extract features from the code to make it accessible for data driven algorithms. Older works usually made use of approaches that used hand-tuned features.

Recent works are inspired by the advances in the the field of Natural Language Processing (NLP), which are caused by neural networks and continuous distributed vectors (referred to as embeddings) e.g., , word2vec [mikolov2013efficient]. Although, human language is different from codes of programming languages in many aspects, embeddings prove to be useful in code related tasks, too.

Code inputs may be used directly in a high-level programming language or in an IR (e.g., , LLVM-IR [LLVM:CGO04]). The advantage of using an IR is that it is independent of the source programming language and the target architecture.

Most approaches for representing high-level language code use some sort of the Abstract Syntax Tree (AST) in combination with various learning mechanisms. Alon et al. [alon2019code2vec] used paths of the AST in combination with a Attention Neural Network model. Others have used the AST in combination with Gated Graph Neural Networks [ye2020deep, allamanis2017learning], with Support Vector Machines [park2012using] or with Long short-term memory (LSTM) Networks for tree structures [dam2018deep].

With Neural Code Comprehension (inst2vec) [ben2018neural], Ben-Nun et al. defined an embedding space for the LLVM-IR. Relevant information to discover code semantics are data and control flow. To emphasize the semantics, the data and control flow are represented in a novel graph structure, called Contextual Flow Graphs (XFGs). The context of an individual statement, with size  $N$ , is defined as the statement and its graph neighbors that are connected by a path of length  $N$ . This statement is then mapped to its embedding by using the skip-gram model [mikolov2013distributed], which are known to work good in NLP tasks. The XFG captures features like data and control dependence's, instructions and data types, which are important for our task.

### ProGraML: Graph-based Deep Learning for Program Optimization and Analysis

[cummins2020programl]

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## Compiler-based graph representations for deep learning models of code

[brauckmann2020compiler]

IR2Vec [keerthy2019ir2vec] is another approach that maps an IR to a embedding space. [...] However, the datatype size, which is important for code optimizations, is abstracted away during the embedding process.

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## 2.5 Applied Machine Learning on Code

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**lthemal Accurate, portable and fast basic block throughput estimation using deep neural networks**

[mendis2019ithemal]

**NeuroVectorizer: End-to-End Vectorization with DeepReinforcement Learning**

[haj2020neurovectorizer]

**From Loop Fusion to Kernel Fusion: A Domain-Specific Approach to Locality Optimization**


[qiao2019loop]

**A Machine Learning Approach for Performance Prediction and Scheduling on Heterogeneous CPUs**

[nemirovsky2017machine]

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how  
IR2Vec  
works



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Potential exploration -> random scheduling

Compare speedup with complexity of the problem (number of possible schedulings) vs speedup

Compare CPU Architectures, In-Order vs Out-Of-Order ([https://en.wikipedia.org/wiki/Out-of-order\\_execution](https://en.wikipedia.org/wiki/Out-of-order_execution))



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# Acronyms

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**AST** Abstract Syntax Tree

**NLP** Natural Language Processing

**IR** Intermediate Representation

**XFG** Contextual Flow Graph

**LSTM** Long short-term memory