Code Generation for Data Processing

Lecture 1: Introduction and Interpretation

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Module "Code Generation for Data Processing"

Learning Goals

- Getting from an intermediate code representation to machine code
- Designing and implementing IRs and machine code generators
- Apply for: JIT compilation, query compilation, ISA emulation

Prerequisites

- Computer Architecture, Assembly — ERA, GRA/ASP
- Databases, Relational Algebra — GDB
- Beneficial: Compiler Construction, Modern DBs

Topic Overview

Introduction

- Introduction and Interpretation
- Compiler Front-end

Intermediate Representations

- IR Concepts and Design
- LLVM-IR
- LLVM Transforms and Analyses

Compiler Back-end

- Instruction Selection
- Register Allocation
- Linker, Loader, Debuginfo

Applications

- JIT-compilation + Sandboxing
- Query Compilation
- Binary Translation

Lecture Organization

- Lecturer: Dr. Alexis Engelke `engelke@in.tum.de`
- Time slot: Thu 10-14, 02.11.018
- Material: `https://db.in.tum.de/teaching/ws2223/codegen/`

Exam

- Written exam, 90 minutes, **no retake**, date TBD
- (Might change to oral on very low registration count)

Exercises

- Weekly homework, often with programming exercise
- Submission via e-mail: `engelke+cghomework@in.tum.de`
  - Probably no explicit grading, feedback on best effort
- Exercise sessions to present and discuss solutions

Grade Bonus

- Requirement: $N - 2$ "sufficiently working" homework submissions **and** at least 2 presentations of homework in class
- Bonus: grades in $[1.3; 4.0]$ improved by 0.3

Why study compilers?

- Critical component of every system, functionality and performance
  - Compiler mostly *alone* responsible for using hardware well
- Brings together many aspects of CS:
  - Theory, algorithms, systems, architecture, software engineering, (ML)
- New developments/requirements pose new challenges
  - New architectures, environments, language concepts, ...
- High complexity!

Compiler Lectures @ TUM

Compiler Construction IN2227, SS, THEO
Front-end, parsing, semantic analyses, types

Program Optimization IN2053, WS, THEO
Analyses, transformations, abstract interpretation

Virtual Machines IN2040, SS, THEO
Mapping programming paradigms to IR/bytecode

Programming Languages CIT3230000, WS
Implementation of advanced language features

Code Generation CIT3230001, WS
Back-end, machine code generation, JIT comp.

Why study code generation?

- Frameworks (LLVM, ...) exist and are comparably good, but often not good enough (performance, features)
  - Many systems with code gen. have their own back-end
  - E.g.: V8, WebKit FTL, .NET RyuJIT, GHC, Zig, QEMU, Umbra, ...
- Machine code is not the only target: bytecode
  - Often used for code execution
  - E.g.: V8, Java, .NET MSIL, BEAM (Erlang), Python, MonetDB, eBPF, ...
  - Allows for flexible design
  - But: efficient execution needs machine code generation

Proebsting's Law

"Compiler advances double computing power every *18* years."

– Todd Proebsting, 1998[1]

- Still optimistic; depends on number of abstractions

[1] http://proebsting.cs.arizona.edu/law.html

Motivational Example: Brainfuck

- Turing-complete esoteric programming language, 8 operations
  - Input/output: `.` `,`
  - Moving pointer over infinite array: `<` `>`
  - Increment/decrement: `+` `-`
  - Jump to matching bracket if (not) zero: `[` `]`

```
++++++[->++++++<]>.
```

- Execution with pen/paper? ☹

Program Execution

Programs

- High flexibility (possibly)
- Many abstractions (typically)
- Several paradigms

Hardware/ISA

- Low-level interface
- Few operations, imperative
- "Not easy" to write

Motivational Example: Brainfuck – Interpretation

- Write an interpreter!

```
unsigned char state[10000];
unsigned ptr = 0, pc = 0;
while (prog[pc])
  switch (prog[pc++]) {
  case '.': putchar(state[ptr]); break;
  case ',': state[ptr] = getchar(); break;
  case '>': ptr++; break;
  case '<': ptr--; break;
  case '+': state[ptr]++; break;
  case '-': state[ptr]--; break;
  case '[': state[ptr] || (pc = matchParen(pc, prog)); break;
  case ']': state[ptr] && (pc = matchParen(pc, prog)); break;
  }
```

Program Execution

Compiler

Program → Compiler → Program

- Translate program to other lang.
- Might optimize/improve program

- C, C++, Rust → machine code
- Python, Java → bytecode

Interpreter

Program → Interpreter → Result

- Directly execute program
- Computes program result

- Shell scripts, Python bytecode, machine code (conceptually)

- Multiple compilation steps can precede the “final interpretation”

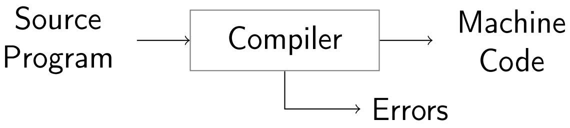
Compilers

- Targets: machine code, bytecode, or other source language
- Typical goals: better language usability and performance
  - Make lang. usable at all, faster, use less resources, etc.

- Constraints: specs, resources (comp.-time, etc.), requirements (perf., etc.)

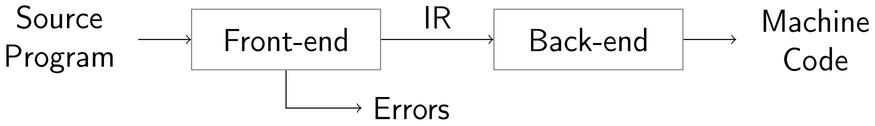
- Examples:
  - "Classic" compilers source → machine code
  - JIT compilation of JavaScript, WebAssembly, Java bytecode, ...
  - Database query compilation
  - ISA emulation/binary translation

Compiler Structure: Monolithic



- Inflexible architecture, hard to retarget

Compiler Structure: Two-phase architecture



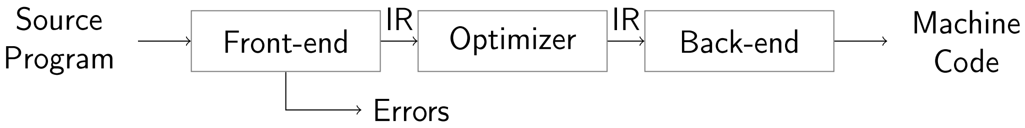
Front-end

- Parses source code
- Detect syntax/semantical errors
- Emit *intermediate representation* encode semantics/knowledge
- Typically: $\mathcal{O}(n)$ or $\mathcal{O}(n \log n)$

Back-end

- Translate IR to target architecture
- Can assume valid IR ($\rightsquigarrow$ no errors)
- Possibly one back-end per arch.
- Contains $\mathcal{NP}$-complete problems

Compiler Structure: Three-phase architecture



- Optimizer: analyze/transform/rewrite program inside IR

- Conceptual architecture: real compilers typically much more complex
  - Several IRs in front-end and back-end, optimizations on different IRs
  - Multiple front-ends for different languages
  - Multiple back-ends for different architectures

Compiler Front-end

1. Tokenizer: recognize words, numbers, operators, etc. $\mathcal{R}e$
   - Example: `a+b*c` $\rightarrow$ `ID(a) PLUS ID(b) TIMES ID(c)`
2. Parser: build (abstract) syntax tree, check for syntax errors $\mathcal{CFG}$
   - Syntax Tree: describe grammatical structure of complete program
     Example: `expr("a", op("+"), expr("b", op("*"), expr("c"))`
   - Abstract Syntax Tree: only relevant information, more concise
     Example: `plus("a", times("b", "c"))`
3. Semantic Analysis: check types, variable existence, etc.
4. IR Generator: produce IR for next stage
   - This might be the AST itself

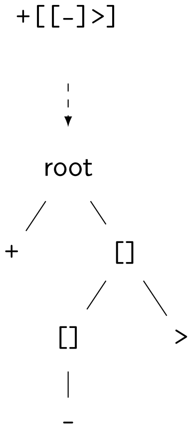
Compiler Back-end

1. Instruction Selection: map IR operations to target instructions
   - Use target features: special insts., addressing modes, ...
   - Still using virtual/unlimited registers
2. Instruction Scheduling: optimize order for target arch.
   - Start memory/high-latency earlier, etc.
   - Requires knowledge about micro-architecture
3. Register Allocation: map values to fixed register set/stack
   - Use available registers effectively, minimize stack usage

Motivational Example: Brainfuck – Front-end

- Need to skip comments
- Bracket searching is expensive/redundant

- Idea: “parse” program!
- Tokenizer: yield next operation, skipping comments
- Parser: find matching brackets, construct AST



Motivational Example: Brainfuck – AST Interpretation

- AST can be interpreted recursively

```c
struct node { char kind; int cldCnt; struct node* cld; };
struct state { unsigned char* arr; size_t ptr; };
void donode(struct node* n, struct state* s) {
  switch (n->kind) {
  case '+': s->arr[s->ptr]++; break;
  // ...
  case '[': while (s->arr[s->ptr]) children(n); break;
  case 0: children(n); break; // root
  }
}
void children(struct node* n, struct state* s) {
  for (int i = 0; i < n->cldCnt; i++) donode(n->cld + i, s);
}
```

Motivational Example: Brainfuck – Optimization

- Inefficient sequences of `+`/`-`/`<`/`>` can be combined
  - Trivially done when generating IR
- Fold patterns into more high-level operations
  - `[-]` = set zero
  - `[>]` = find next zero (`memchr`)
  - `[->+>+«]` = add to next two siblings, set zero
  - `[->+++<]` = add 3 times to next sibling, set zero
  - ...

Motivational Example: Brainfuck – Optimization

- Fold offset into operation
  - `right(2) add(1)` = `addoff(2, 1) right(2)`
  - Also possible with loops
- Analysis: does loop move pointer?
  - Loops that keep position intact allow more optimizations
  - Maybe distinguish "regular loops" from arbitrary loops?
- Get rid of all "effect-less" pointer movements
- Combine arithmetic operations, disambiguate addresses, etc.

Motivational Example: Brainfuck – Bytecode

- Tree is nice, but rather inefficient $\rightsquigarrow$ flat and compact bytecode
- Avoid pointer dereferences/indirections; keep code size small

- Superinstructions: combine common sequences to one instruction
- Maybe dispatch two instructions at once?
  - `switch (ops[pc] | ops[pc] << 8)`

Motivational Example: Brainfuck – Threaded Interpretation

- Simple `switch–case` dispatch has lots of branch misses
- Threaded interpretation: at end of a handler, jump to next op

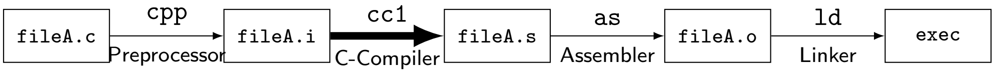
```
struct op { char op; char data; };
struct state { unsigned char* arr; size_t ptr; };
void threadedInterp(struct op* ops, struct state* s) {
    static const void* table[] = { &&CASE_ADD, &&CASE_RIGHT, };
#define DISPATCH do { goto *table[(++pc)->op]; } while (0)

    struct op* pc = ops;
    DISPATCH;

CASE_ADD: s->arr[s->ptr] += pc->data; DISPATCH;
CASE_RIGHT: s->arr += pc->data; DISPATCH;
}
```

Fast Interpretation

- Key technique to “avoid” compilation to machine code
- Preprocess program into efficiently executable bytecode
  - Easily identifiable opcode, homogeneous structure
  - Can be linear (fast to execute), but trees also work
- Perhaps optimize – if it’s worth the benefit
  - Fold constants, combine instructions, . . .
  - Consider superinstructions for common sequences
- For very cold code: avoid transformations at all
- Use threaded-interpretation to avoid branch misses

Compiler: Surrounding – Compile-time

- Typical environment for a C/C++ compiler:



- Calling Convention: interface with other objects/libraries
- Build systems, dependencies, debuggers, etc.
- Compilation target machine (hardware, VM, etc.)

Compiler: Surrounding – Run-time

- OS interface (I/O, . . .)
- Memory management (allocation, GC, . . .)
- Parallelization, threads, . . .
- VM for execution of virtual assembly (JVM, . . .)
- Run-time type checking
- Error handling: exception unwinding, assertions, . . .
- Reflection, RTTI

Motivational Example: Brainfuck – Runtime Environment

- Needs I/O for . and ,
- Memory management: infinitely sized array
- Allocate on demand (easy?)
  - What if main memory or address space is insufficient?
- Deallocation of empty pages?
- Error handling: unmatched brackets

Compilation point: AoT vs. JIT

Ahead-of-Time (AoT)

- All code has to be compiled
- No dynamic optimizations
- Compilation-time secondary concern

Just-in-Time (JIT)

- Compilation-time is critical
- Code can be compiled on-demand
  - Incremental optimization, too
- Handle cold code fast
- Dynamic specializations possible
- Allows for `eval()`

Various hybrid combinations possible

Compiler Design: Effect of Languages – Imperative

- Step-by-step execution of program modification of state
- Close to hardware execution model
- Direct influence of result

- Tracking of state is complex
- Dynamic typing: more complexity
- Limits optimization possibilities

```
void addvec(int* a, const int* b) {
  for (unsigned i = 0; i < 4; i++)
    a[i] += b[i]; // vectorizable?
}
```

```
func:
  mov [rdi], rsi
  mov [rdi+8], rdx
  mov [rdi], 0 // redundant?
  ret
```

Compiler Design: Effect of Languages – Declarative

- Describes execution target
- Compiler has to derive good mapping to imperative hardware

- Allows for more optimizations
- Mapping to hardware non-trivial
  - Might need more stages
  - Preserve semantic info for opt!
- Programmer has less “control”

```
select s.name
from studenten s
where exists (select 1
              from hoeren h
              where h.matrno=s.matrno)
```

```
let rec fac = function
    | 0 | 1 -> 1
    | n -> n * fac (n - 1)
```

Introduction and Interpretation – Summary

- Compilation vs. interpretation and combinations
- Compilers are key to usable/performant languages
- Target language typically machine code or bytecode
- Three-phase architecture widely used
- Interpretation techniques: bytecode, threaded interpretation, ...
- JIT compilation imposes different constraints

Introduction and Interpretation – Questions

- What is typically compiled and what is interpreted? Why?
  - PostScript, C, JavaScript, HTML, SQL
- What are typical types of output languages of compilers?
- How does a compiler IR differ from the source input?
- What is the impact of the language paradigm on optimizations?
- What are important factors for an efficient interpreter?
- What are key differences between AoT and JIT compilation?