Compilers and computer architecture: introduction

Martin Berger [1]

Thanks to Chad MacKinney, Alex Jeffery, Justin Crow, Jim Fielding, Shaun Ring and Vilem Liepelt for suggestions and corrections. Thanks to Benjamin Landers for the RARS simulator.
Thanks to Alex Aiken for his Compiler MOOC that this course was heavily inspired by.

September 2019

[1] Email: `M.F.Berger@sussex.ac.uk`, Office hours: Wed 12-13 in Chi-2R312.

Administrative matters: lecturer

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- Assessment: coursework (50%) and by unseen examination (50%). Both courseworks involve writing parts of a compiler. Due dates for courseworks: Fri, 8 Nov 2019, and Fri, 20 Dec 2019, both 18:00.

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Please, ask questions ...

- during the lesson
- at the end of the lesson
- in my office hours (see `https://users.sussex.ac.uk/~mfb21/cal` for available time-slots)
- by email `M.F.Berger@sussex.ac.uk`
- on Canvas
- in the tutorials
- in the course's Discord channel (invite is on Canvas)
- any other channels (e.g. Telegram, TikTok ...)?

Please, don't wait until the end of the course to tell me about any problems you may encounter.

Prerequisites

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Good Java programming skills are indispensable.This course is **not** about teaching you how to program. “Good” in this context means you can do most questions on e.g.

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classified as “Easy” without problems (= without looking up the answer, and in 1 hour or less). I also recommed that you familiarise yourself with the material on “Shell Tools and Scripting” and “Command-line Environment” in:

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It helps if you have already seen a CPU, e.g. know what a register is or a stack pointer.

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This will take approximately 9 weeks, so we have time at the end for some advanced material. I’m happy to tailor the course to your interest, so please let me know what you want to hear about.

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- Fairness. Automatic testing removes subjective element.

Note that if you make a basic error in your compiler then it is quite likely that **every** test fails and you will get 0 points. So it is really important that you test your code before submission thoroughly. I encourage you to share tests and testing frameworks with other students: as tests are not part of the deliverable, you make share them. Of course the compiler must be written by yourself.

Plan for today's lecture

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Whirlwind overview of the course.

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To understand low-level languages (assembler, C/C++, Rust, Go) better. Those languages are of prime importance, e.g. for writing operating systems, embedded code and generally code that needs to be fast (e.g. computer games, ML e.g. TensorFlow).

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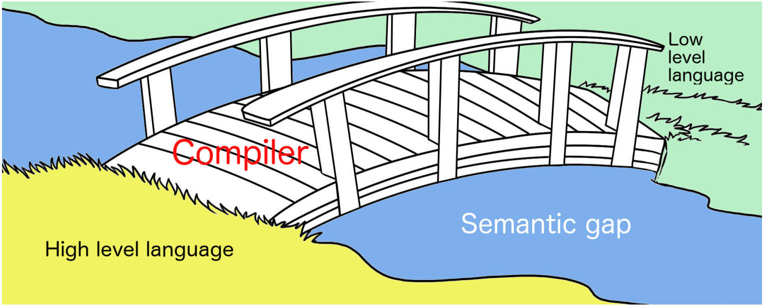
But most of all: compilers are extremely amazing, beautiful and one of the all time great examples of human ingenuity. After 70 years of refinement compilers are a paradigm case of beautiful software structure (modularisation). I hope it inspires you.

Overview: what is a compiler?



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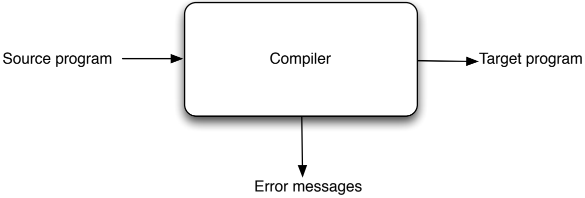

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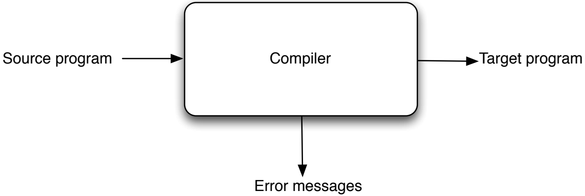

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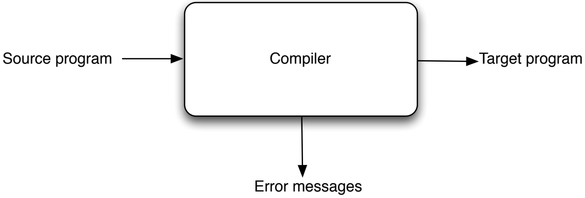

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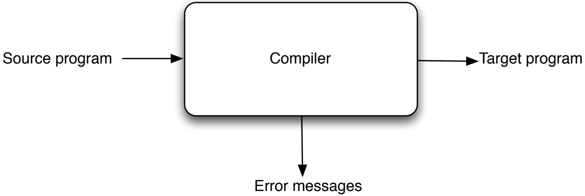

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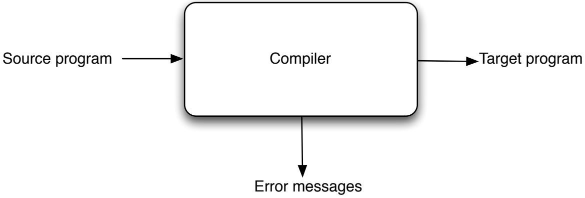

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- Source: JVM bytecode, target: ARM/x86 machine code

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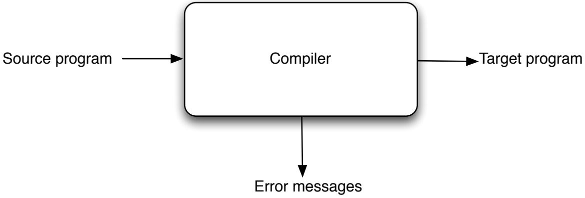

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Examples

- Source: Java, target: JVM bytecode.
- Source: JVM bytecode, target: ARM/x86 machine code
- Source: TensorFlow, target: GPU/TPU machine code.

Example translation: source program

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Here is a little program. (What does it do?)

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int testfun( int n ){
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Using `clang -S` this translates to the following x86 machine code ...

Example translation: target program

```
_testfun:                               ## @testfun
        .cfi_startproc
                                        ## BB#0:
        pushq   %rbp
Ltmp0:
        .cfi_def_cfa_offset 16
Ltmp1:
        .cfi_offset %rbp, -16
        movq    %rsp, %rbp
Ltmp2:
        .cfi_def_cfa_register %rbp
        movl    %edi, -4(%rbp)
        movl    $1, -8(%rbp)
LBB0_1:                                 ## =>This Inner Loop Header: Depth=1
        cmpl    $0, -4(%rbp)
        jle     LBB0_3

                                        ## BB#2:
                                        ##   in Loop: Header=BB0_1 Depth=1
        movl    -4(%rbp), %eax
        addl    $4294967295, %eax       ## imm = 0xFFFFFFFF
        movl    %eax, -4(%rbp)
        movl    -8(%rbp), %eax
        shll    $1, %eax
        movl    %eax, -8(%rbp)
        jmp     LBB0_1
LBB0_3:
        movl    -8(%rbp), %eax
        popq    %rbp
        retq
        .cfi_endproc
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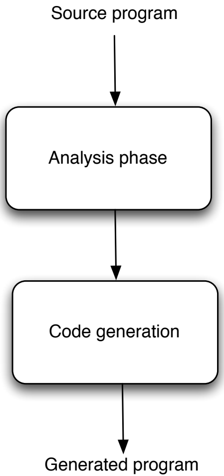

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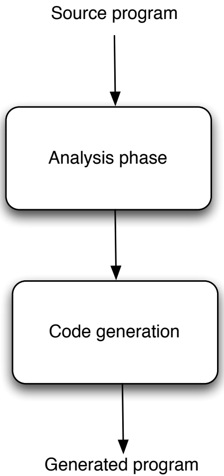

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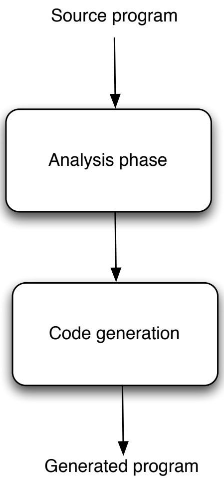

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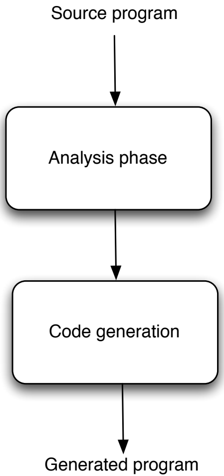

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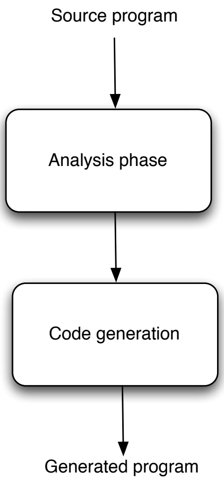

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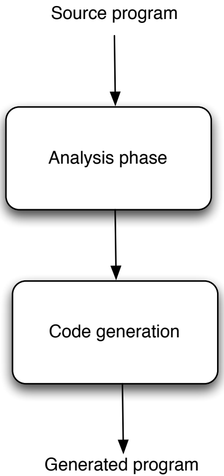

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Let's refine this.

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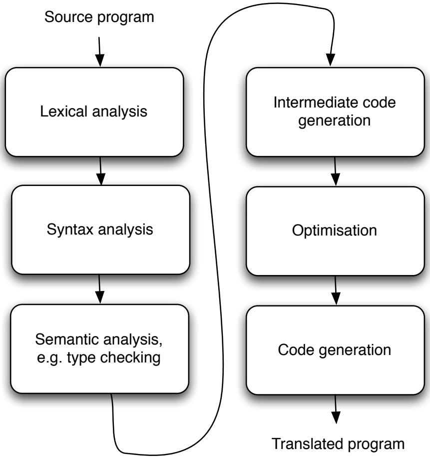

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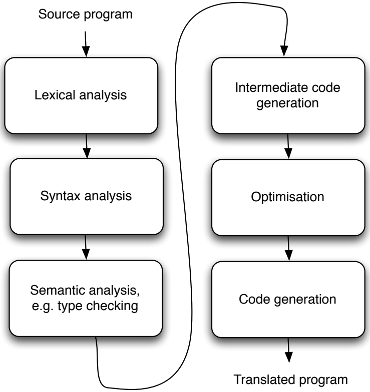

Interesting question: when do these phases happen?

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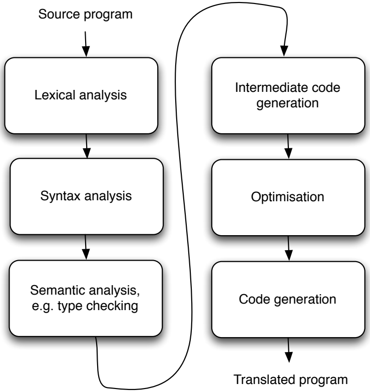

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In the past, all happend at ... compile-time. Now some happen at run-time in Just-in-time compilers (JITs). This has profound influences on choice of algorithms and performance.

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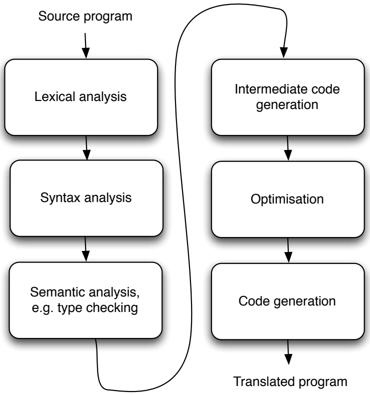

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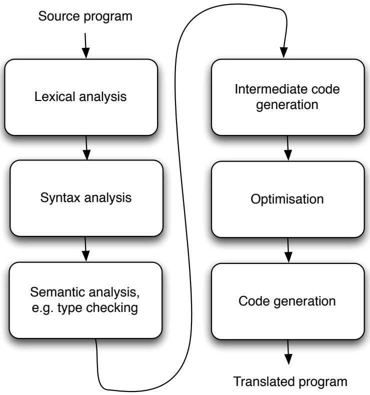

Another interesting question: do you note some thing about all these phases?

The phases are purely functional, in that they take one input, and return one output. Modern programming languages like Haskell, Ocaml, F#, Rust or Scala are ideal for writing compilers.

Phases: Overview

- Lexical analysis
- Syntactic analysis (parsing)
- Semantic analysis (type-checking)
- Intermediate code generation
- Optimisation
- Code generation

Phases: Lexical analysis

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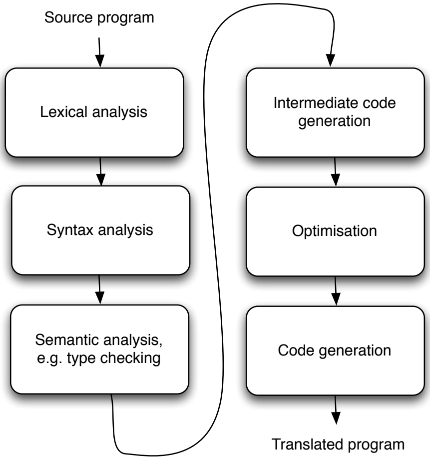

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Strings are not an efficient data-structure for a compiler to work with (= generate code from). Instead, compilers generate code from a more convenient data structure called “abstract syntax trees” (ASTs). We construct the AST of a program in two phases:

- Lexical anlysis. Where the input string is converted into a list of tokens.
- Parsing. Where the AST is constructed from a token list.

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Is (could be) represented as the list

```
T_int, T_ident ( "testfun" ), T_left_brack,
T_int, T_ident ( "n" ), T_rightbrack,
T_left_curly_brack, T_int, T_ident ( "res" ),
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Why is this interesting?

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- Makes the next phase (parsing) much easier.

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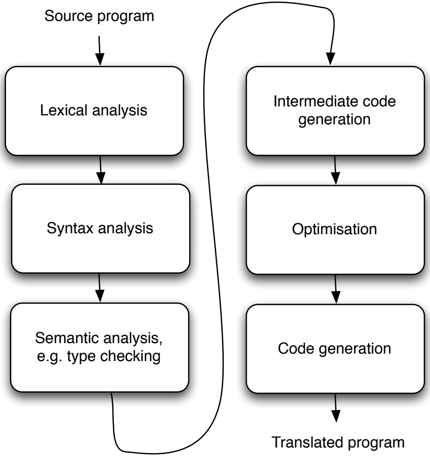

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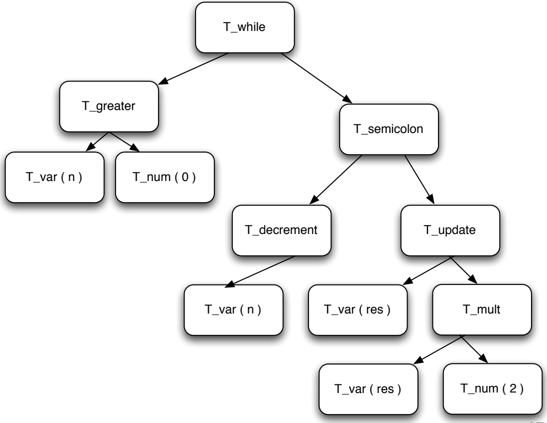

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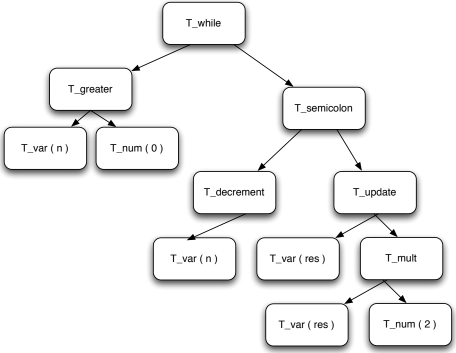

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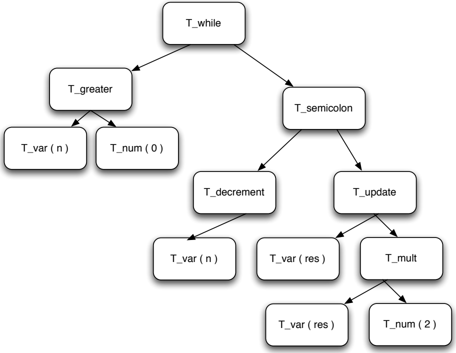

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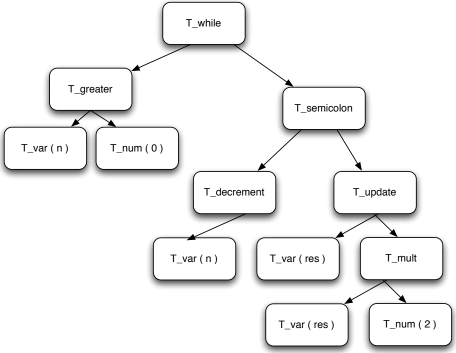

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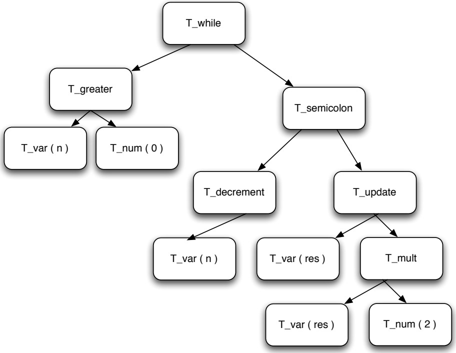

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- The compiler writer must design the AST data structure carefully so that it is easy to build (during syntax analysis), and easy to walk (during code generation).
- The performance of the compiler strongly depends on the AST, so a lot of optimisation goes here for instustrial strength compilers.

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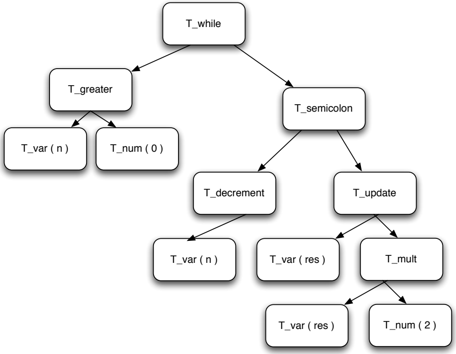

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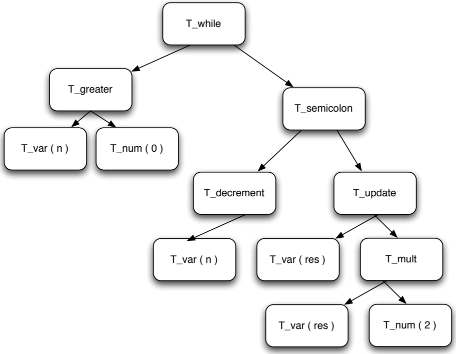

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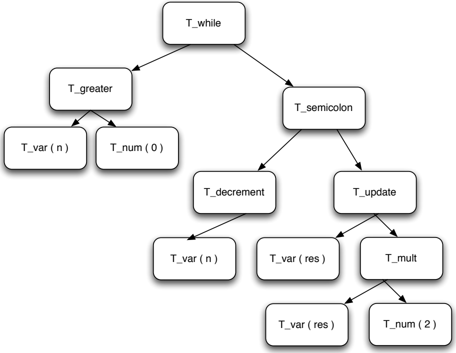

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This dual role is because the rules for constructing the AST are essentially exactly the rules that determine the set of syntactically valid programs. Here the theory of formal languages (context free, context sensitive, and finite automata) is of prime importance. We will study this in detail.

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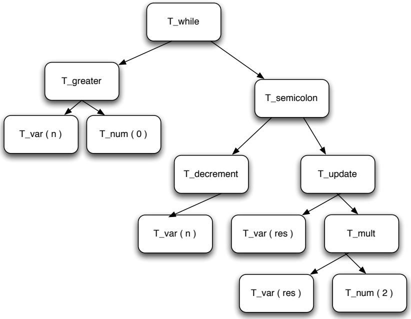

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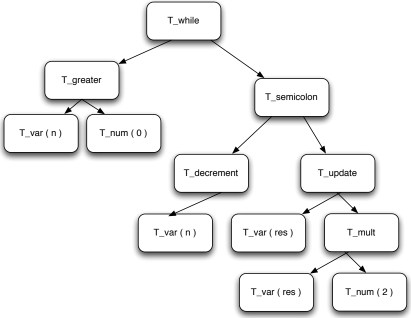

Great news: the generation of lexical analysers and parsers can be automated by using **parser generators** (e.g. lex, yacc). Decades of research have gone into parser generators, and in practise they generate better lexers and parsers than most programmers would be able to. Alas, parser generators are quite complicated beasts, and in order to understand them, it is helpful to understand formal languages and lexing/parsing. The best way to understand this is to write a toy lexer and parser.

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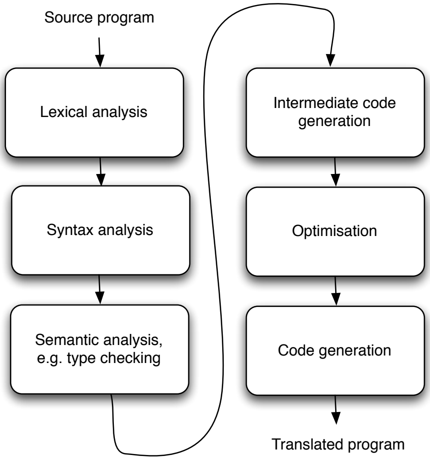

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They are caught with semantic analysis. The key technology are types. Modern languages like Scala, Rust, Haskell, Ocaml, F# employ type inference.

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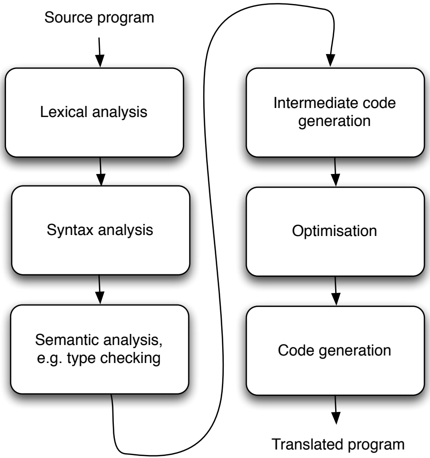

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There are many different CPUs with different machine languages. Often the machine language changes subtly from CPU version to CPU version. It would be annoying if we had to rewrite large parts of the compiler. Fortunately, most machine languages are rather similar. This helps us to abstract almost the whole compiler from the details of the target language. The way we do this is by using in essence two compilers.

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- If we want to retarget the compiler to a new machine language, only this last step needs to be rewritten. Nice data abstraction.

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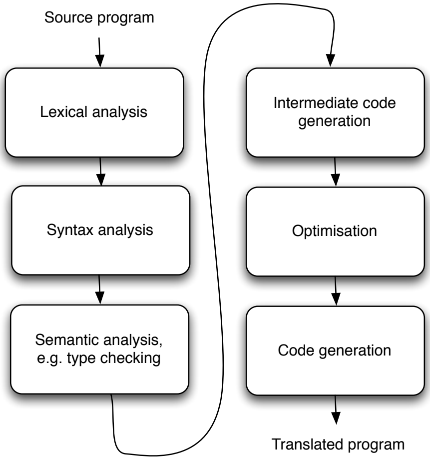

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Translating a program often introduces various inefficiencies, make the program e.g. run slow, or use a lot of memories, or use a lot of power (important for mobile phones). Optimisers try to remove these inefficiencies, by replacing the inefficient program with a more efficient version (without changing the meaning of the program).

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However, some optimisations are easy, e.g. inlining of functions: if a function is short (e.g. computing sum of two numbers), replacing the call to the function with its code, can lead to faster code. (What is the disadvantage of this?)

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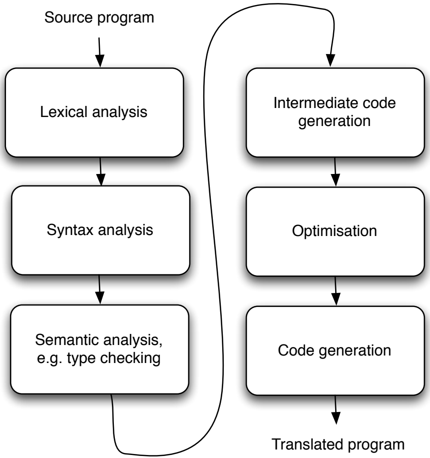

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This straighforward phase translates the generated intermediate code to machine code. As machine code and intermediate code are much alike, this ’mini-compiler’ is simple and fast.

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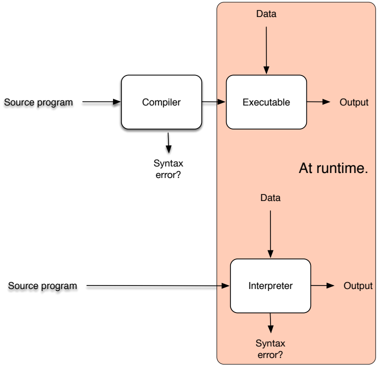

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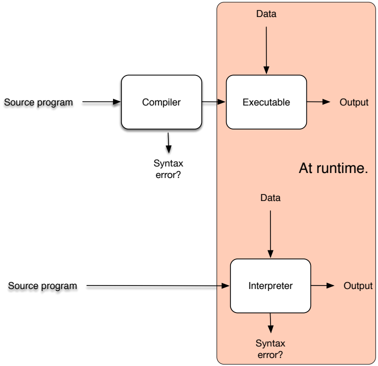

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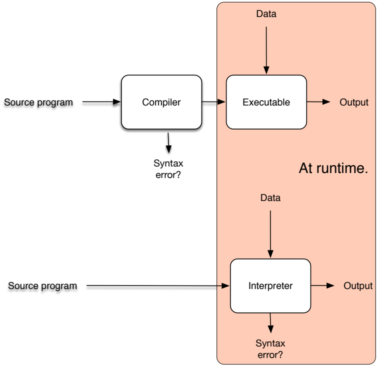

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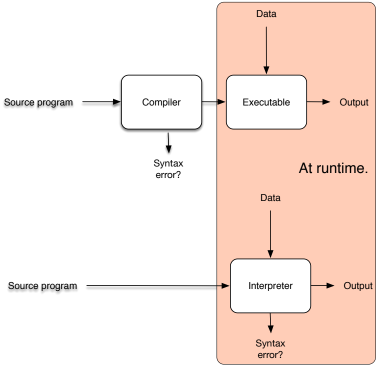

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We won't say much more about interpreters in this course.

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- **Compilers - Principles, Techniques and Tools** (second edition) by Alfred V. Aho, Monica Lam, Ravi Sethi, and Jeffrey D. Ullman. The first edition of this book is is the classic text on compilers, known as the "Dragon Book", but its first edition is a bit obsolete. The second edition is substantially expanded and goes well beyond the scope of our course. For my liking, the book is a tad long.

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- **Computer Architecture - A Quantitative Approach** (sixth edition) by John Hennessey and David Patterson. This is the 'bible' for computer architecture. It goes way beyond what is required for our course, but very well written by some of the world's leading experts on computer architecture. Well worth studying.

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- Have a look at real compilers. There are many free, open-source compilers, g.g. GCC, LLVM, TCC, MiniML, Ocaml, the Scala compiler, GHC, the Haskell compiler.

Feedback

In this module, you will receive feedback through:

- The mark and comments on your assessment
- Feedback to the whole class on assessment and exams
- Feedback to the whole class on lecture understanding
- Model solutions
- Worked examples in class and lecture
- Verbal comments and discussions with tutors in class
- Discussions with your peers on problems
- Online discussion forums
- One to one sessions with the tutors

The more questions you ask, the more you participate in discussions, the more you engage with the course, the more feedback you get.

Questions?