EDAN65: Compilers

# Introduction and Overview

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Revised: 2016-08-29

# Course registration

- Confirm by signing the Registration Form
- Prerequisites
  - Object-oriented programming and Java
  - Algorithms and data structures (recursion, trees, lists, hash tables, …)

# Student representatives

- 2 students
- Participate in post course CEQ discussion (Course Experience Questionnaire)

# Course information

- Web page: http://cs.lth.se/edan65
  - will be updated during the course

- Read http://cs.lth.se/edan65/week-by-week
  - to see what to do each week

- Literature
  - Course material, will be made available on the web site
    - Lectures, articles, assignments, exercises
    - Not handed out – print yourself.
  - Textbook
    - A. W. Appel, Jens Palsberg: Modern Compiler Implementation in Java, 2nd Edition, Cambridge University Press, 2002, ISBN: 0-521-82060-X
    - Available as an on-line e-book through Lund University
    - Only part of the book is used. Covers only part of the course.

- Forum (Q&A) using the Piazza system.
- Quizzes using the Moodle system.

# Course structure

- 14 lectures, Mon 13-15, Tue 10-12, varying lecture halls
- Assignment 0, for freshing up on Java and Unix. Do on your own.
- Assignment 1-6. Mandatory.
  - Work in pairs. Use the lecture break or the forum to form pairs.
  - Heavy. Get approved and get help at Lab sessions.
  - Thu 13-15, Thu 15-17, or Fri 10-12. **Sign up by Thursday Sept 1**
  - Lab sessions start next week (but start this week on your work)
  - Assignments prerequisite for doing exam
- Lecture quizzes
  - Do on your own.
- Exercises
  - Do on your own.
- Exam – sign up in advance through LTH system
  - Exam: Friday, Oct 28, 2016
  - Re-exam: Wednesday Dec 21, 2016

# More on the assignments

- Work *together* with your partner on all parts
  - pair programming, switch *frequently* who is typing
  - you need hands-on experience from all parts
- If you get stuck
  - ask on the Piazza forum
  - you are encouraged to give answers to other students on the forum (for general advice, not solutions)
- Both of you should be able to explain all parts of your solution.
- Want to use a git repo? Make it private! Free on BitBucket.

# Estimated typical effort for assignments

| | | |
|---|---|---|
| A0: Unix and Java | 0-2 hours | recommended |
| A1: Scanning | 5 hours | mandatory |
| A2: Parsing | 15 hours | mandatory |
| A3: Visitors, aspects | 12 hours | mandatory |
| A4: Semantic analysis | 18 hours | mandatory |
| A5: Interpreter | 15 hours | mandatory |
| A6: Code generator | 12 hours | mandatory |

# Instructors

- Lectures
  - Prof. Görel Hedin
- Programming assignments and lab sessions
  - Ph. D. student Jesper Öqvist
  - Ph. D. student Alfred Åkesson

# Why learn compiler construction?

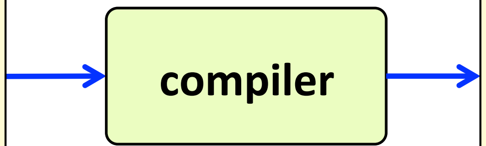
- Very useful in practice
  - Languages are everywhere
  - Your next project might need a small language

- Interesting
  - Compiler theory: fundamental to computer science
  - Essential for understanding programming languages

# A traditional compiler

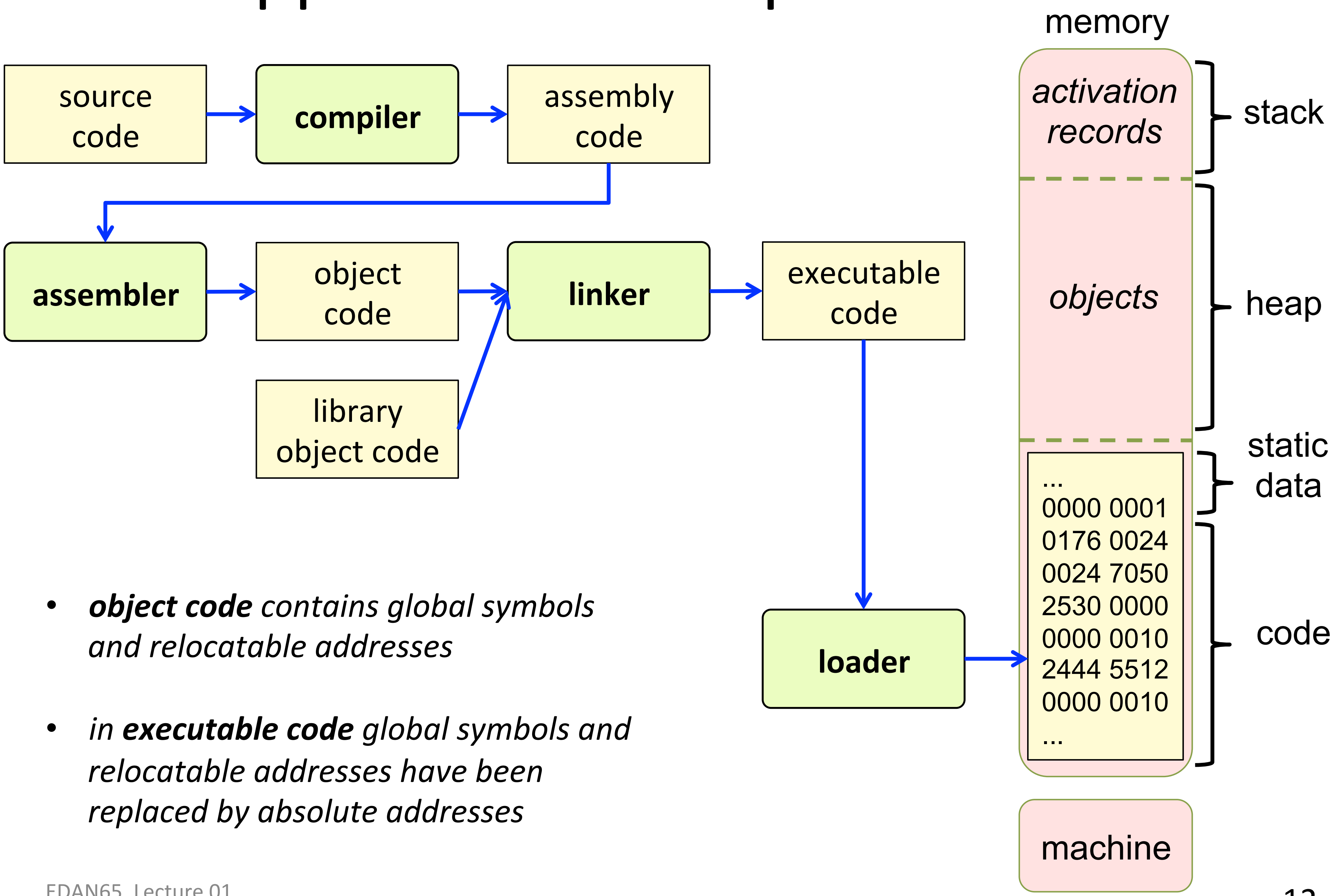

EXAMPLE:

```
...
csum = a + b + 1;
...
```



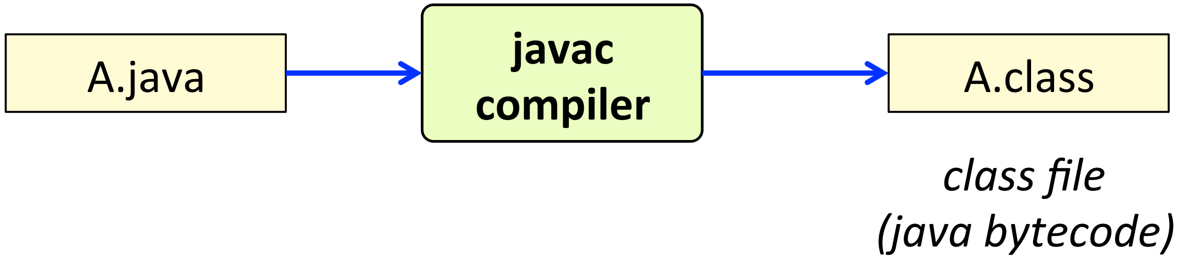

```
        .data
a:      .long   0
b:      .long   0
csum:   .long   0

        .code
        ...
        movl    a, %eax
        addl    b, %eax
        addl    $1, %eax
        movl    %eax, csum
        ...
```

# What happens after compilation?

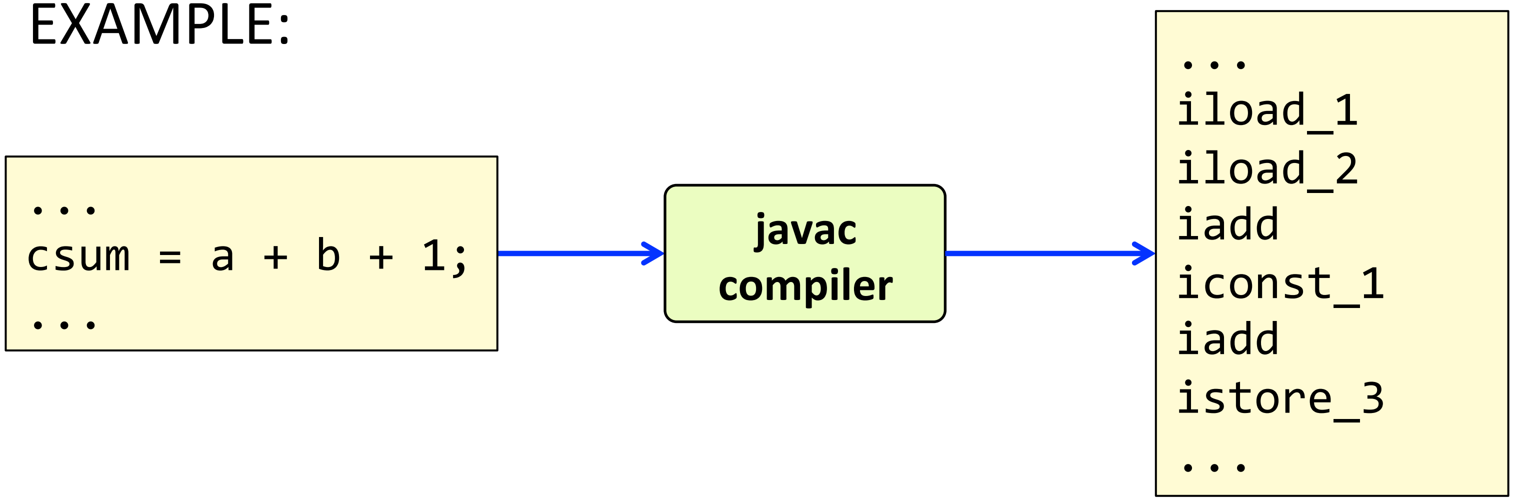



- ***object code*** *contains global symbols and relocatable addresses*
- *in* ***executable code*** *global symbols and relocatable addresses have been replaced by absolute addresses*

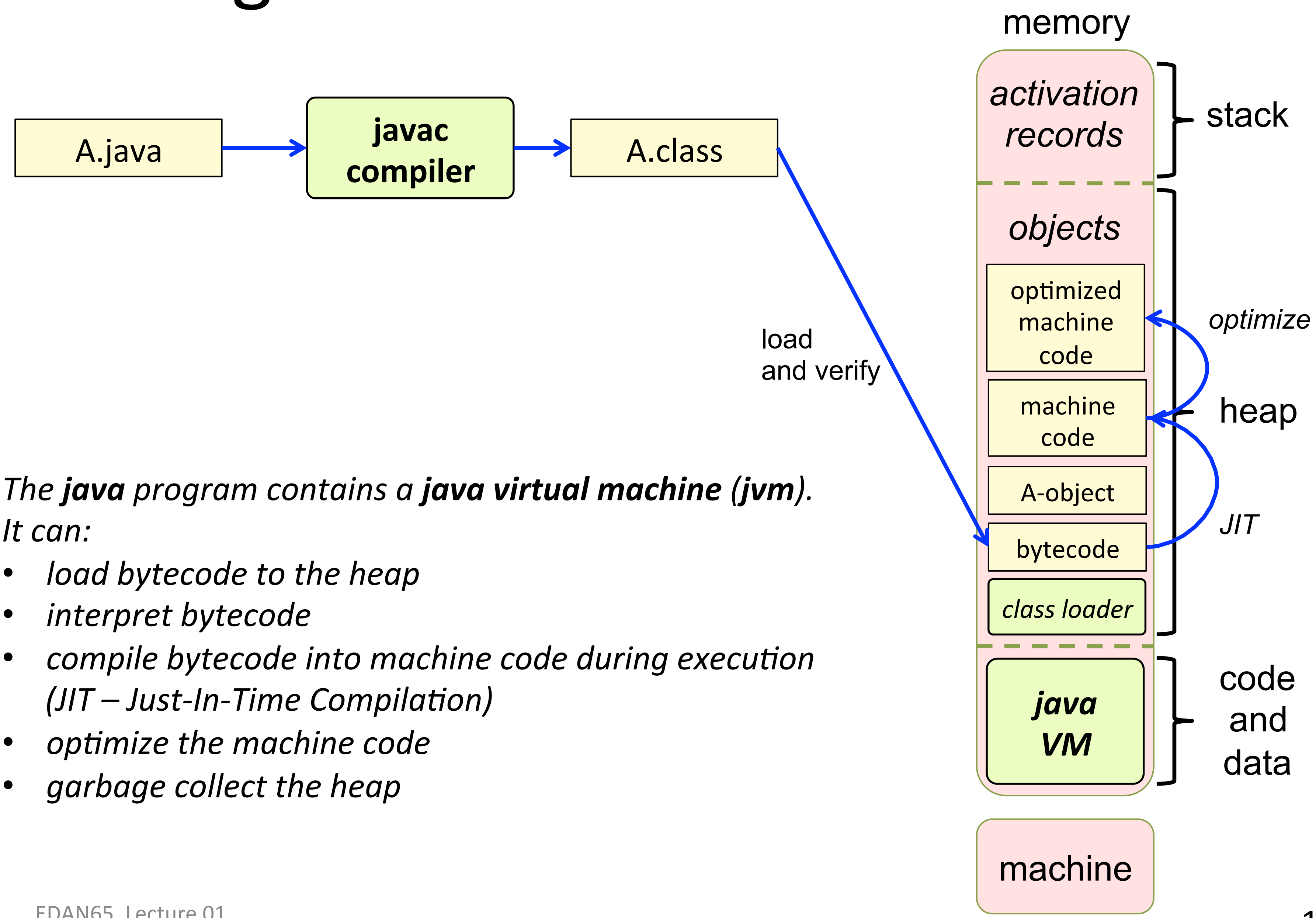
# What about Java?




EXAMPLE:



# Running Java code?

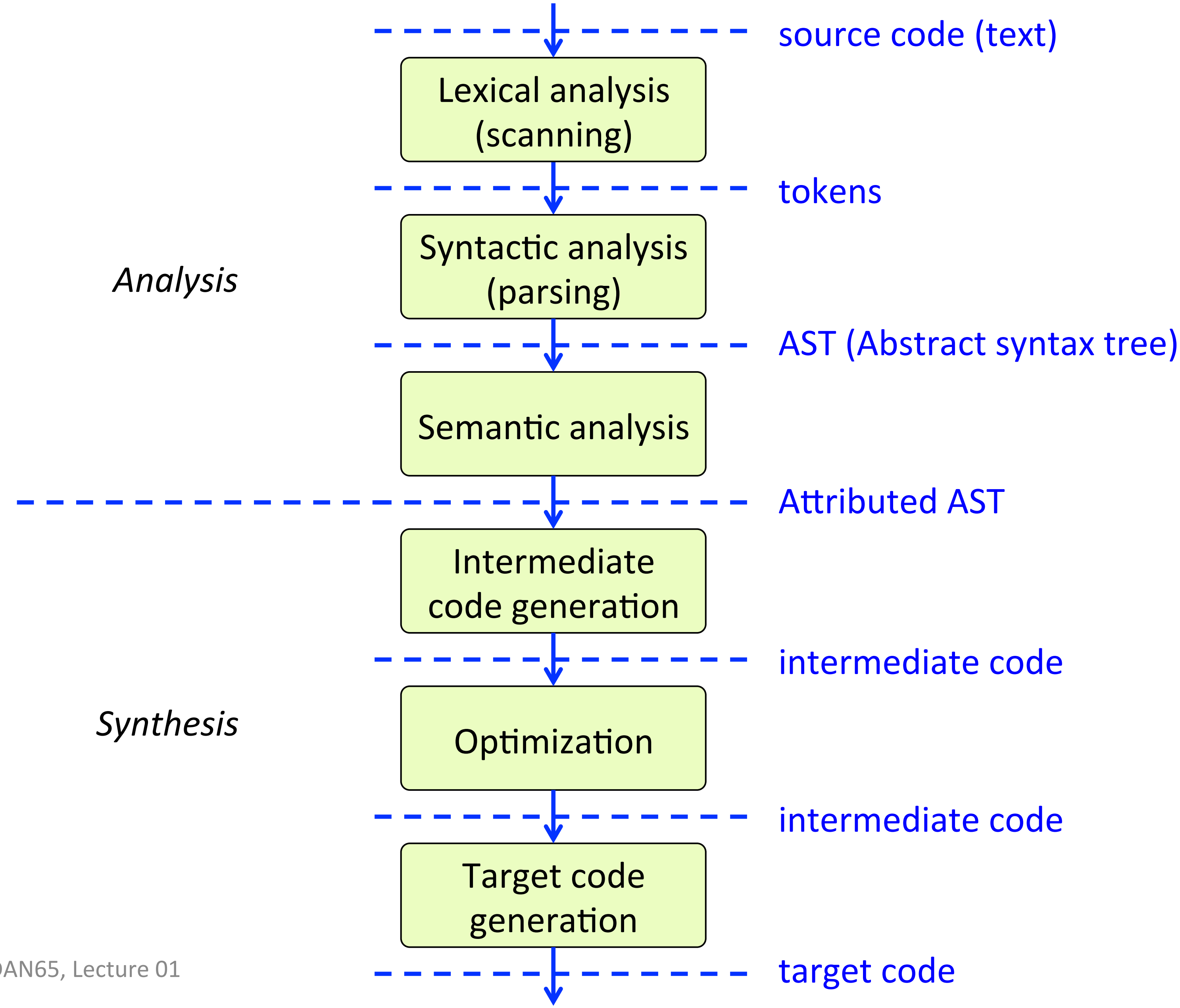



*The **java** program contains a **java virtual machine (jvm)**. It can:*

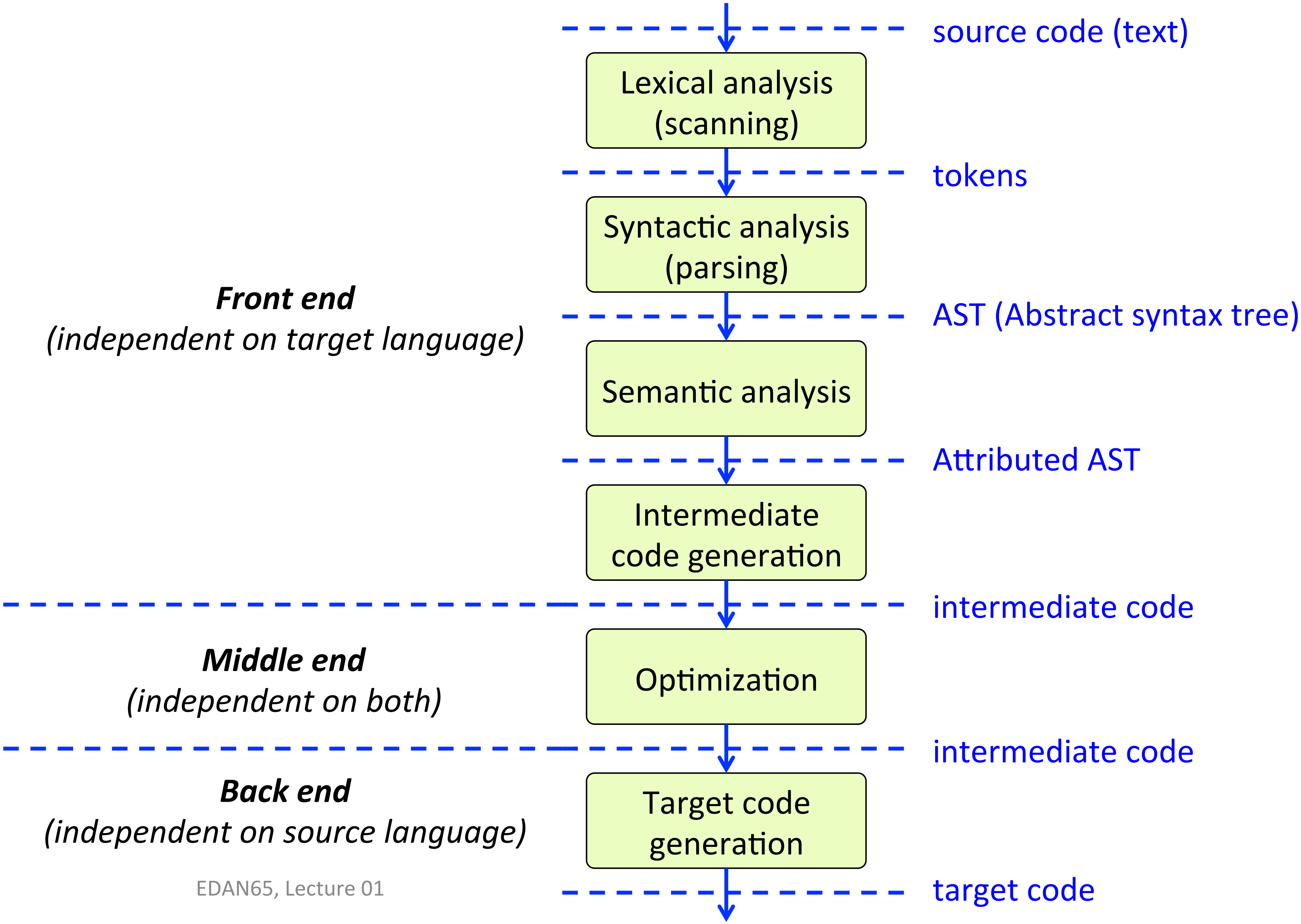
- *load bytecode to the heap*
- *interpret bytecode*
- *compile bytecode into machine code during execution (JIT – Just-In-Time Compilation)*
- *optimize the machine code*
- *garbage collect the heap*

# Inside the compiler:

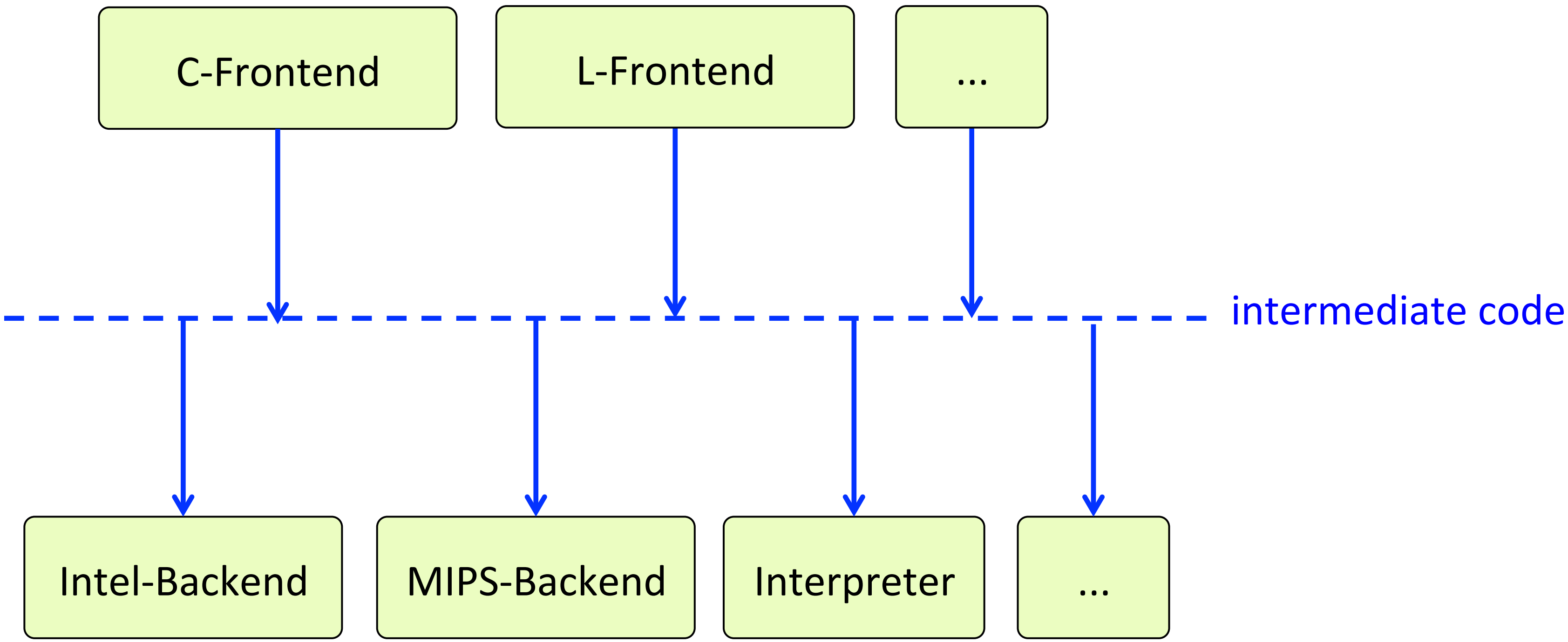
Each ***phase*** converts the program from one ***representation*** to another



# Front and back end:



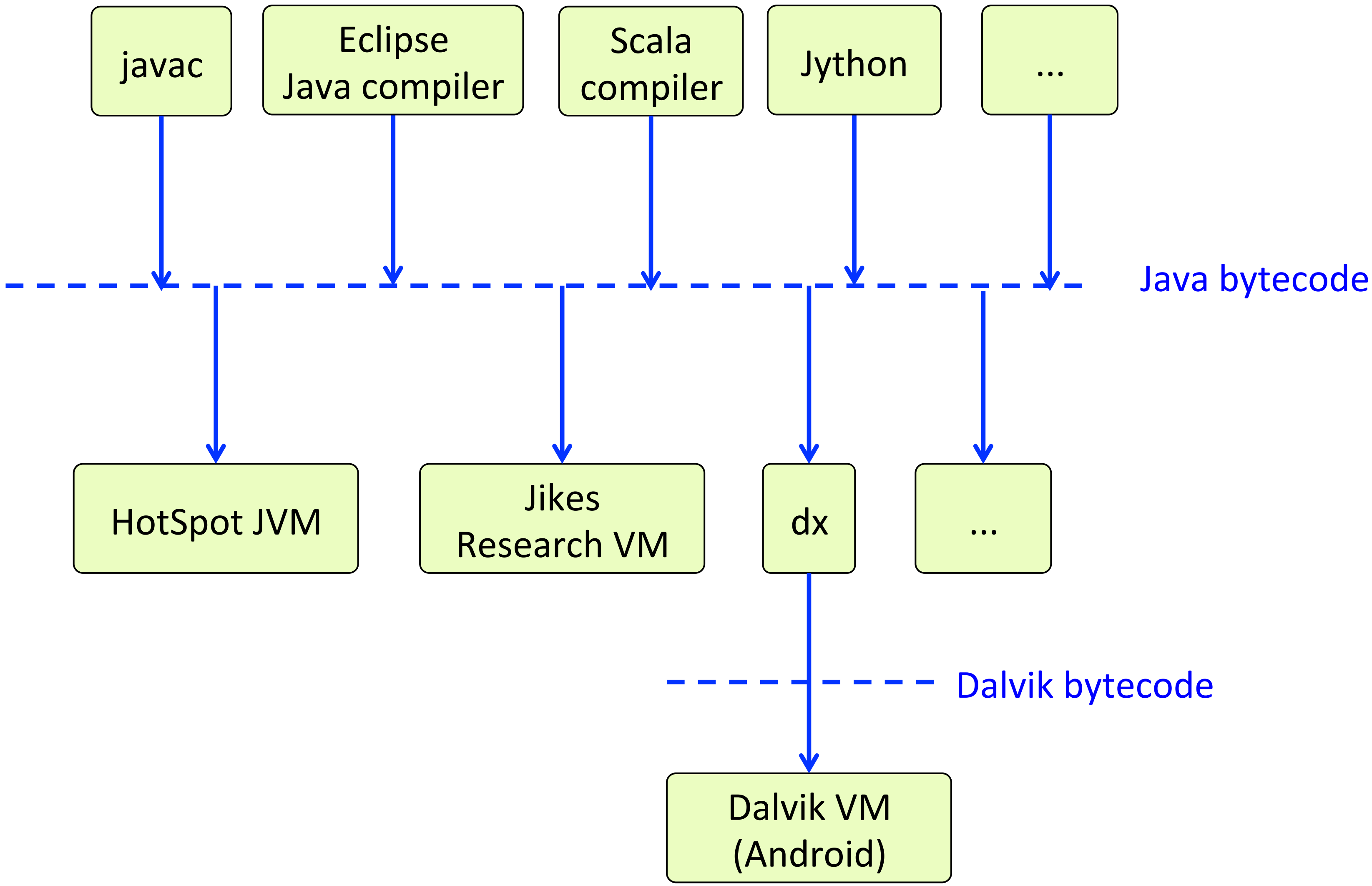
# Several front and back ends:




Why?

- It is more rational to implement m front ends + n back ends than m * n compilers.
- Many optimizations are best performed on intermediate code.
- It may be easier to debug the front end using an interpreter than a target machine

# Example:



javac
Eclipse Java compiler
Scala compiler
Jython
...
Java bytecode
HotSpot JVM
Jikes Research VM
dx
...
Dalvik bytecode
Dalvik VM (Android)

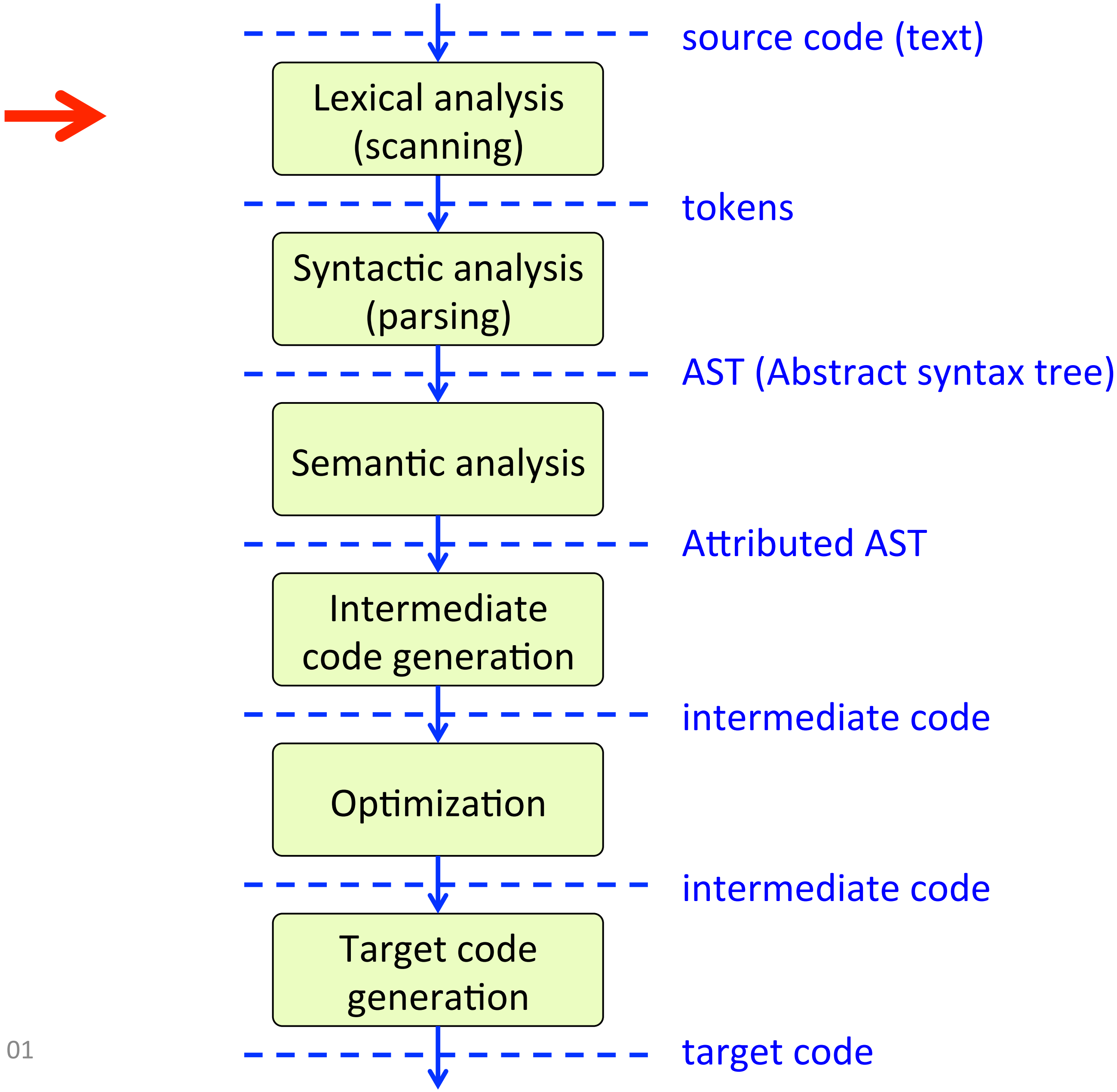
# Some terminology

- A ***compiler*** translates a high-level program to low-level code.
- An ***interpreter*** is software that executes a high/low level program, often by calling one procedure for each program construct.
- In the context of compiler construction, a ***virtual machine (VM)*** is an interpreter that executes low-level, usually platform-independent code. (In other contexts, virtual machine can mean system virtualization.)
- Platform-independent low-level code, designed to be executed by a VM, was originally called ***p-code*** (portable code), but is now usually called ***bytecode***.
- An interpreter or VM may use a ***JIT*** ("just in time") compiler to compile all or parts of the program into machine code during execution.

# Some historical anecdotes

- The first compiler was developed by Grace Hopper in 1952.
- John McCarthy used JIT compilation in his LISP interpreter in 1960. This was called "Compile and Go". The term JIT came later, and was popularized with Java.
- The Pascal-P system, developed by Niklaus Wirth in 1972, used portable code called "p-code". The interpreter was easy to port to different machines. The language spread quickly, and became a popular language taught at many universities.
- Smalltalk-80 used bytecode, and pioneered several runtime compilation and optimization techniques for object-oriented languages.

# Compiler phases and program representations:



# Lexical analysis (scanning)

Source text

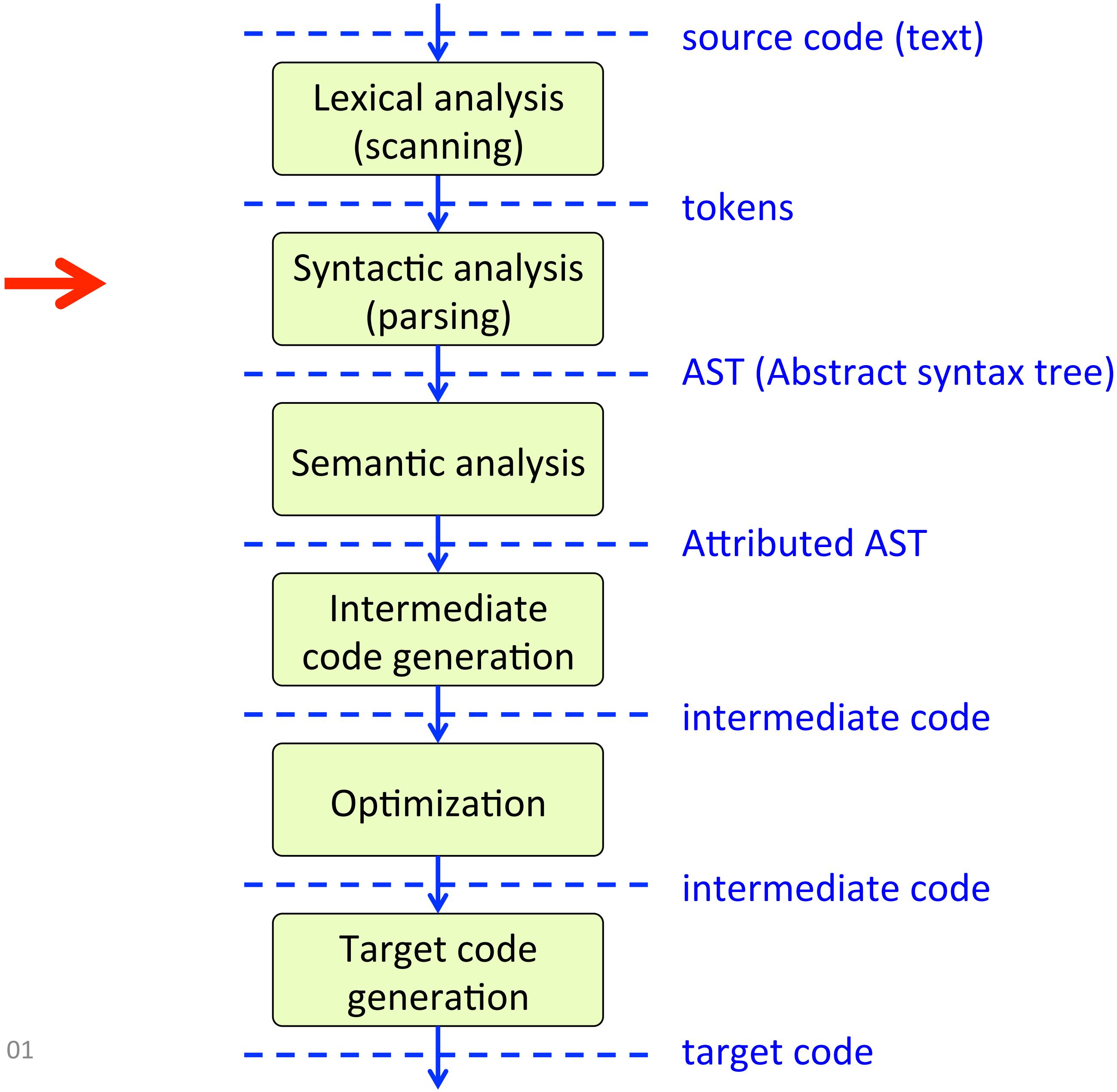
```
while (k<=n) {
  sum=sum+k;
  k=k+1;
}
```

Tokens

```
WHILE LPAR ID(k) LEQ ID(n) RPAR LBRA
ID(sum) EQ ID(sum) PLUS ID(k) SEMI
ID(k) EQ ID(k) PLUS INT(1) SEMI
RBRA
```

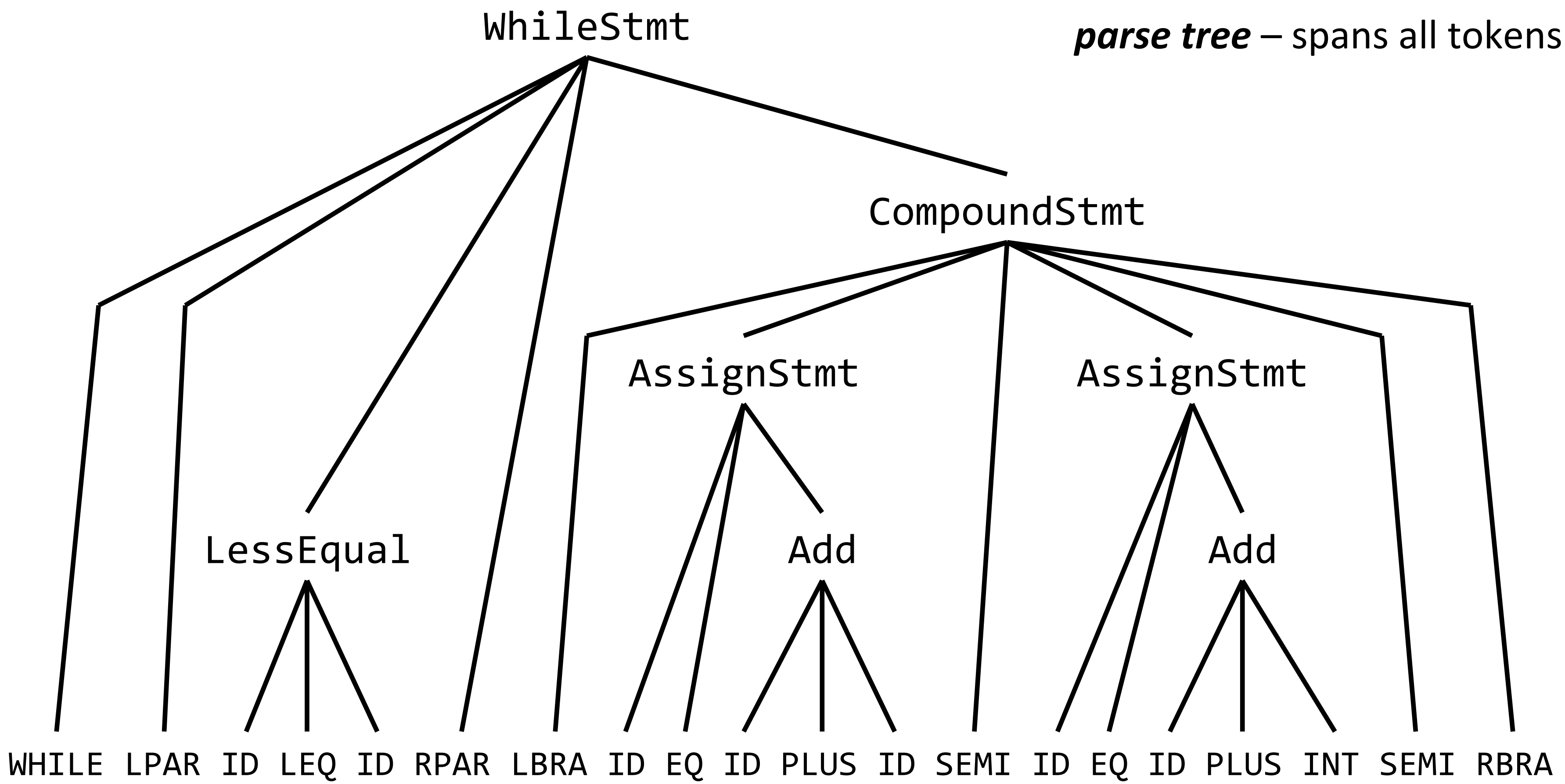
A *token* is a symbolic name, sometimes with an attribute.
A *lexeme* is a string corresponding to a token.

# Compiler phases and program representations:



# Syntactic analysis (parsing)

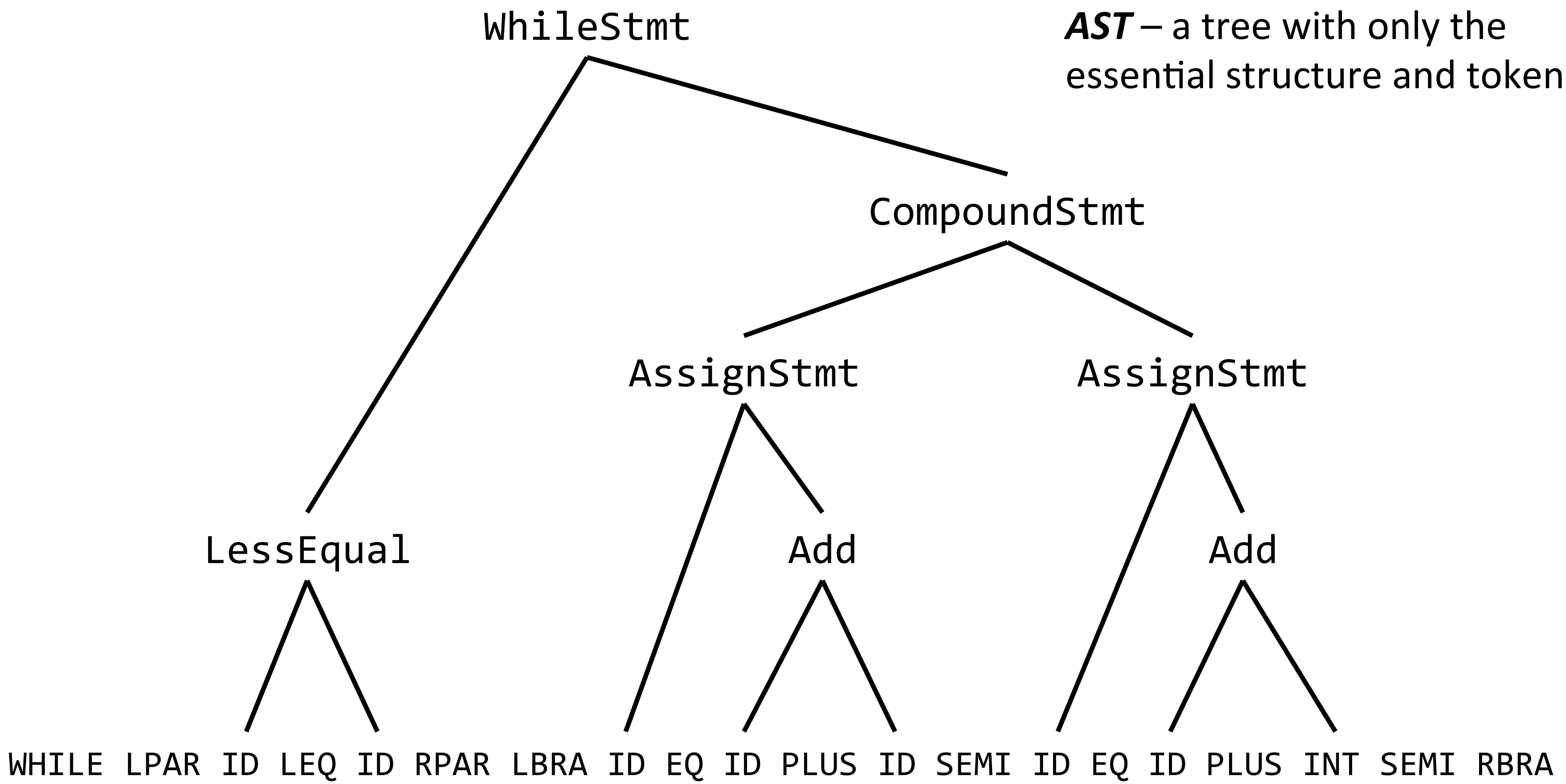
***parse tree*** – spans all tokens




```
while ( k <= n ) { sum = sum + k ; k = k + 1 ; }
```

# Abstract syntax tree (AST)

***AST*** – a tree with only the essential structure and tokens




```
while ( k <= n ) { sum = sum + k ; k = k + 1 ; }
```

# Abstract syntax trees

- Used inside the compiler for representing the program
- Very similar to the parse tree, but
  - contains only essential tokens
  - has a simpler more natural structure
- Often represented by a typed object-oriented model
  - abstract classes (Stmt, Expr, Decl, ...)
  - concrete classes (WhileStmt, IfStmt, Add, Sub, ...)

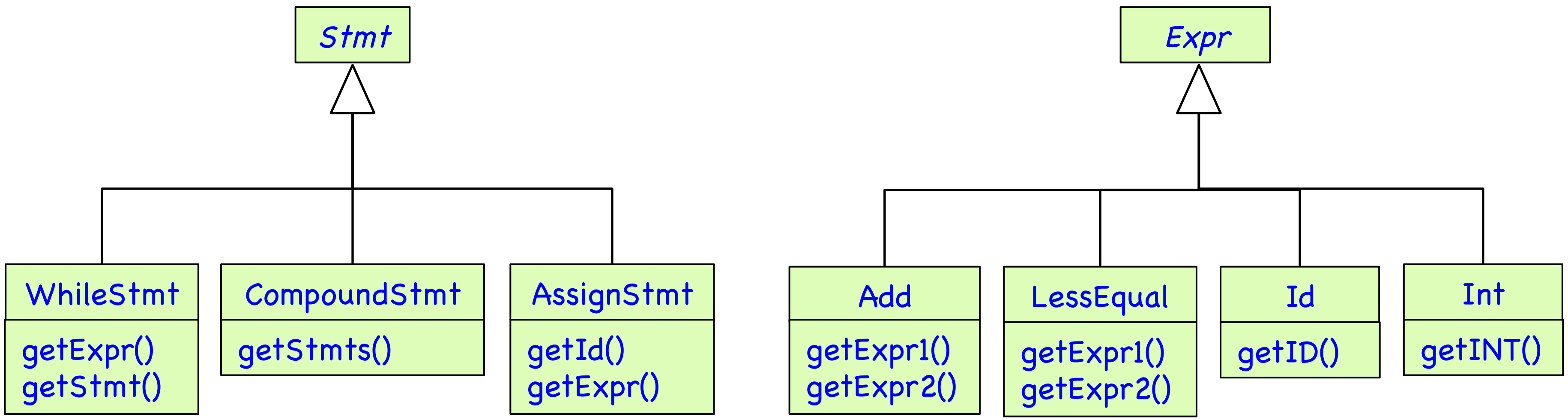
# Designing an AST model (class hierarchy)

- What abstract constructs are there in the language
  - Make them abstract types

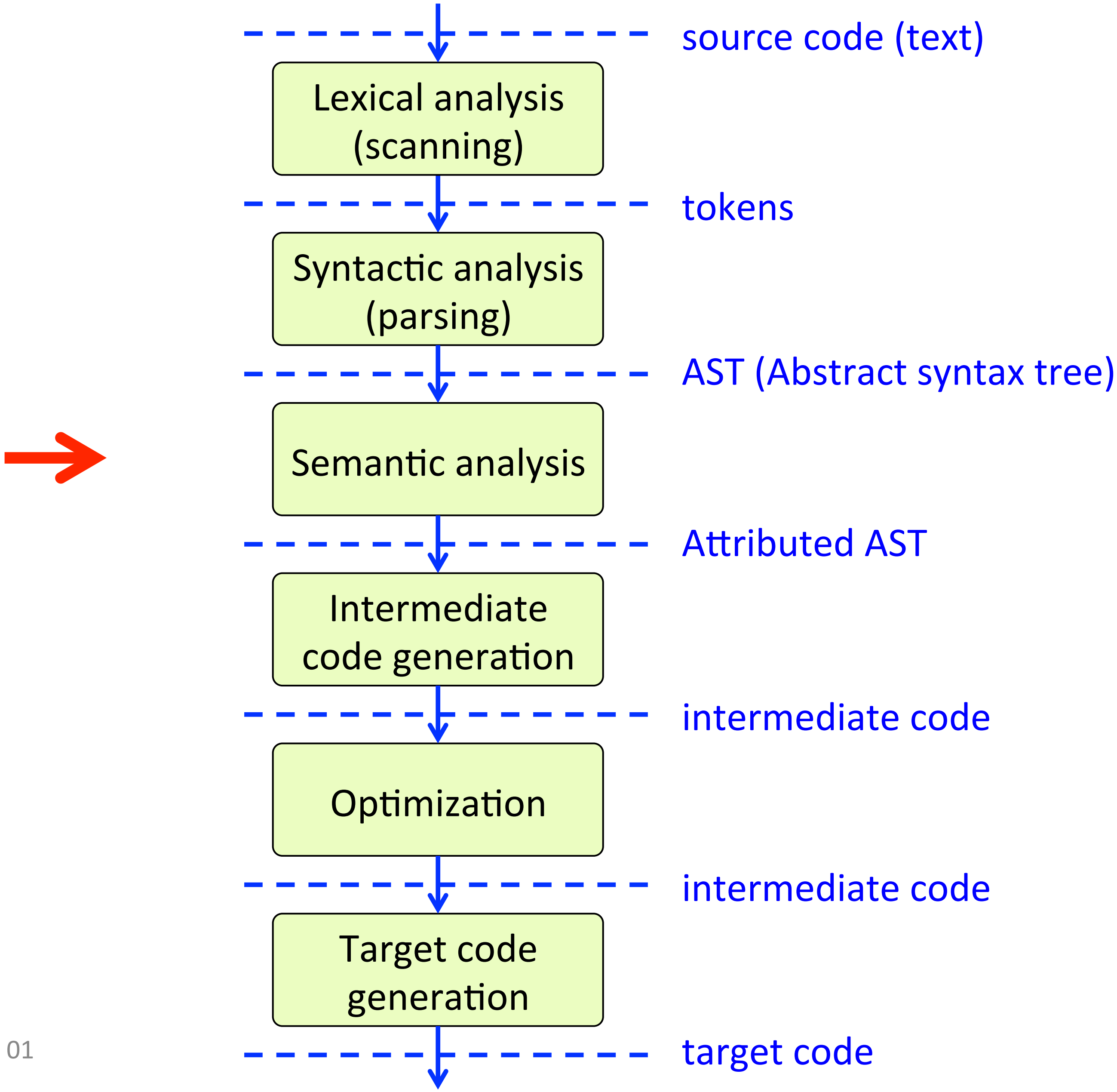
- What concrete constructs are there?
  - Make them subtypes

- What parts do the concrete constructs have?
  - Add getters for them, so the AST can be traversed

# Example AST class hierarchy



# Compiler phases and program representations:



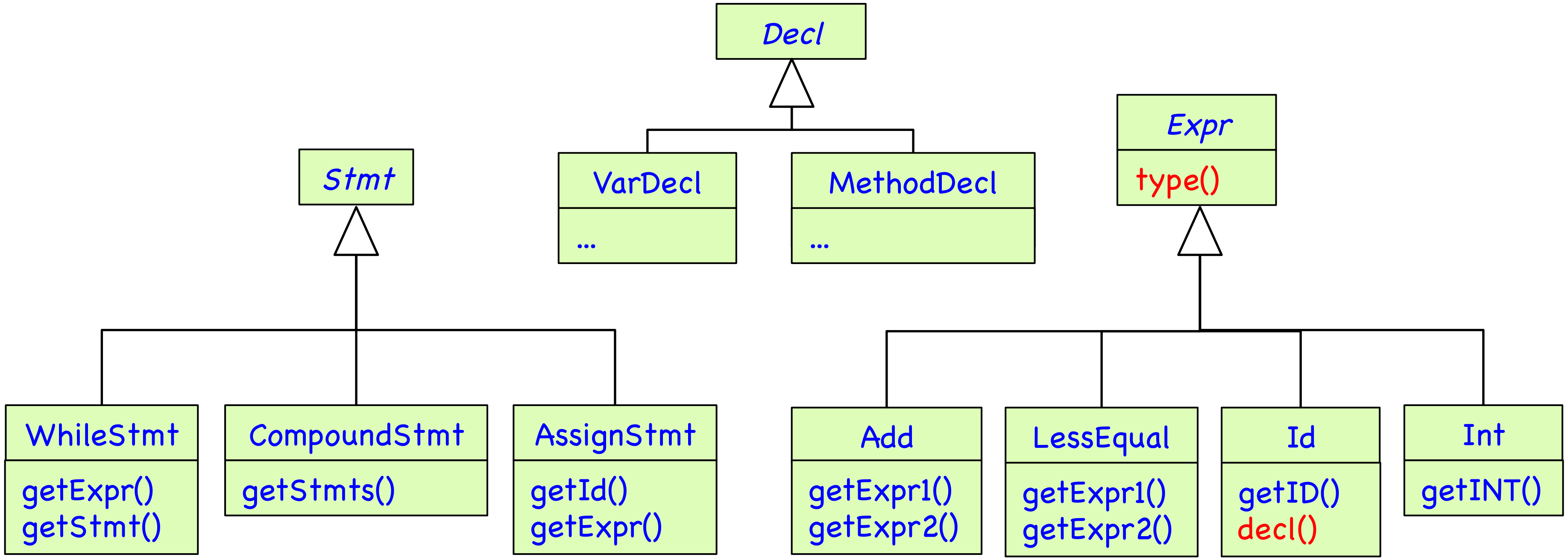
# Semantic analysis

Analyze the AST, for example,

- Which declaration corresponds to a variable?
- What is the type of an expression?
- Are there compile time errors in the program?

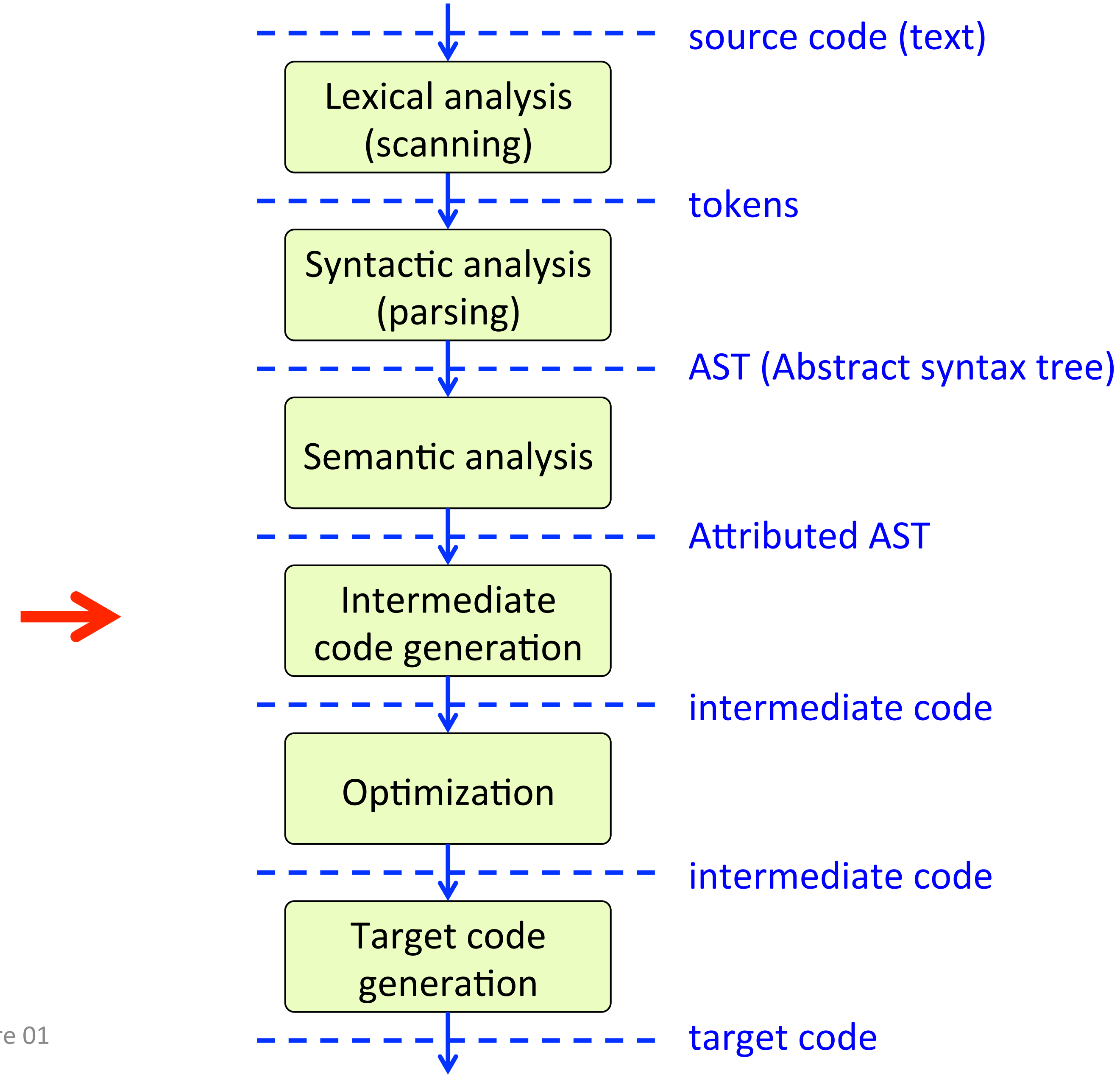
Analysis aided by adding *attributes* to the AST (properties of AST nodes)

# Example attributes




Each Expr has a type() attribute, indicating if the expression is integer, boolean, etc.
Each Id has a decl() attribute, referring to the appropriate declaration node.

# Compiler phases and program representations:

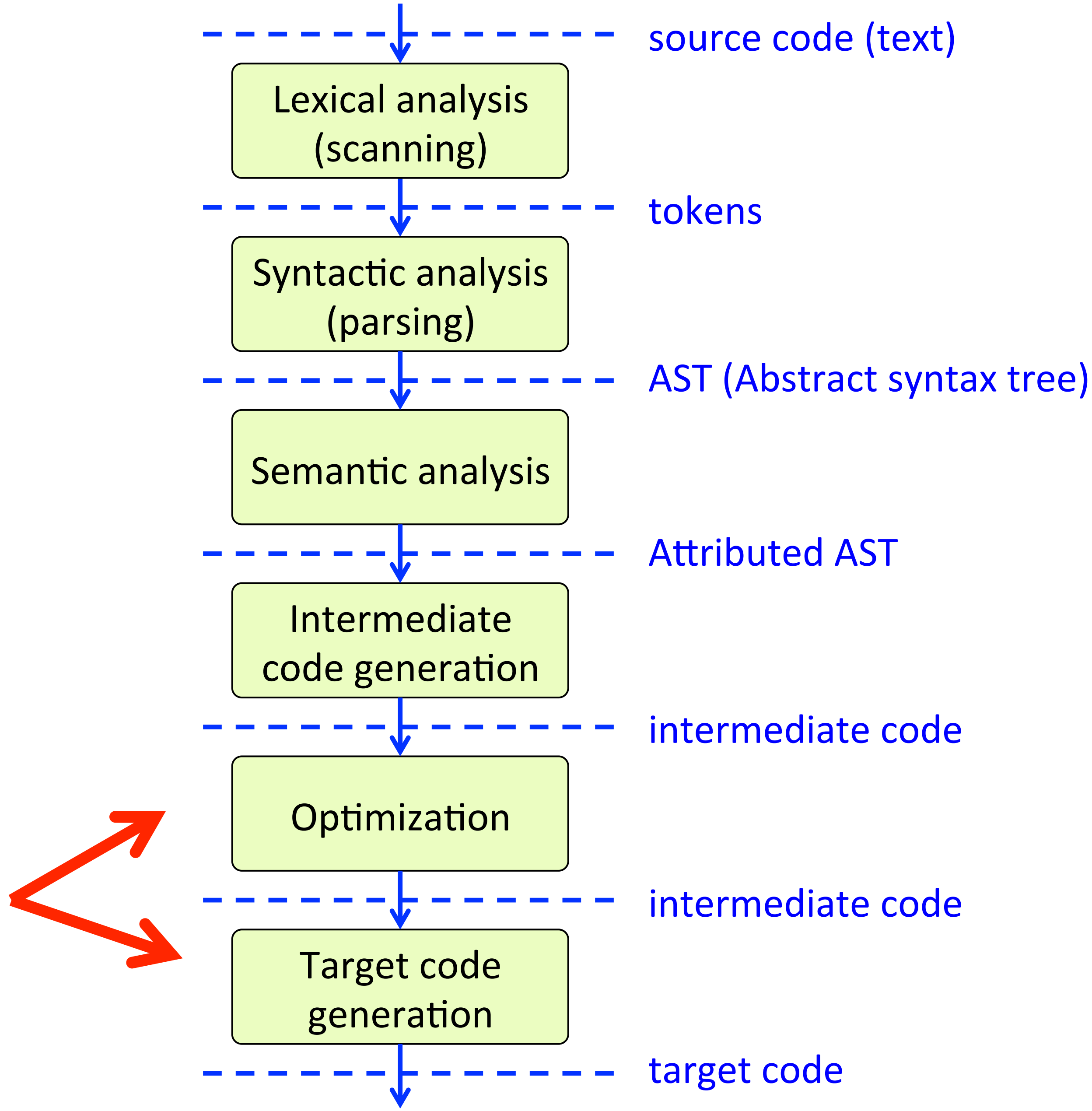


# Intermediate code generation

Intermediate code:

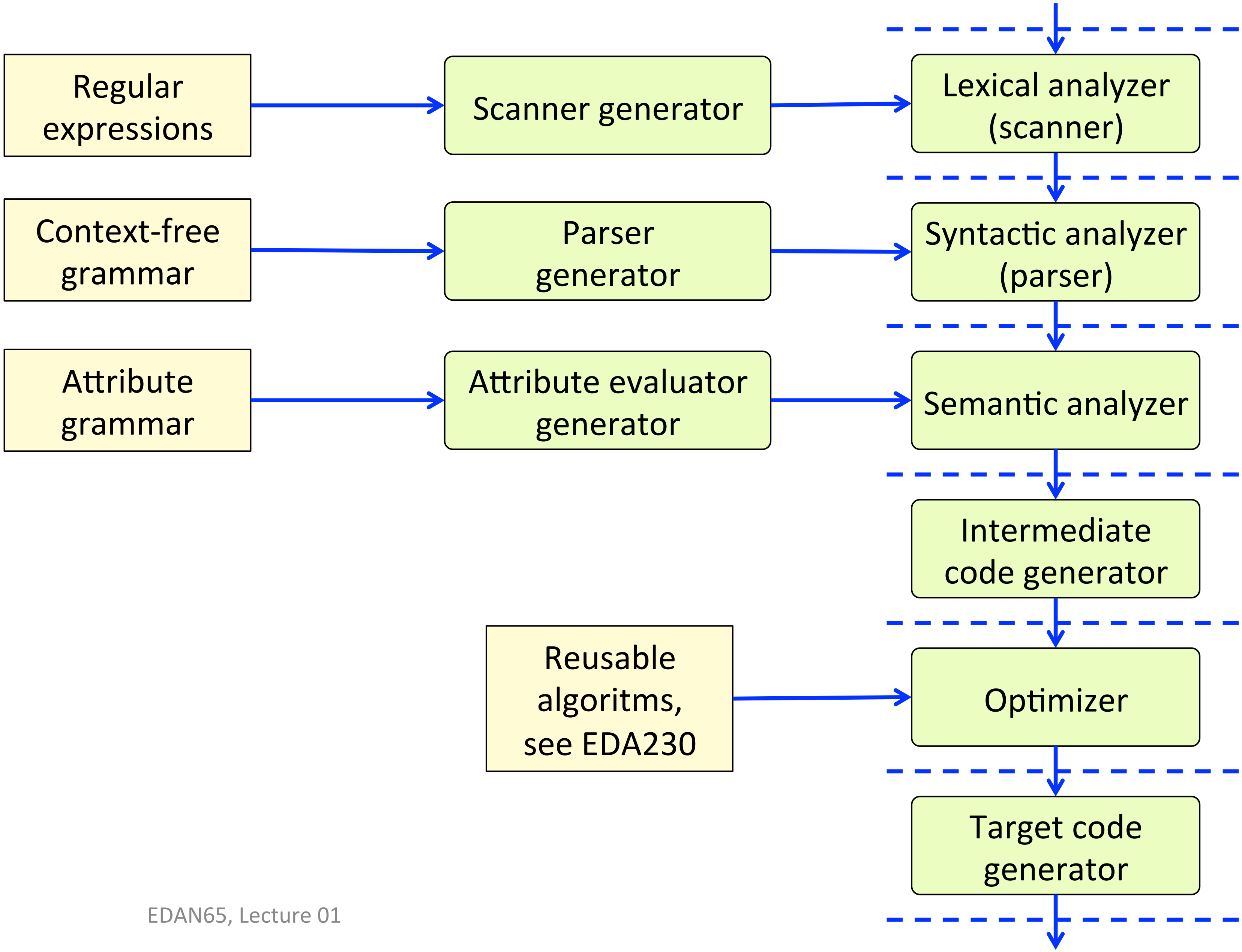
- independent of source language
- independent of target machine
- usually assembly-like
  - but simpler, without many instruction variants
  - and with an unlimited number of registers
    (or uses a stack instead of registers)

# Compiler phases and program representations:

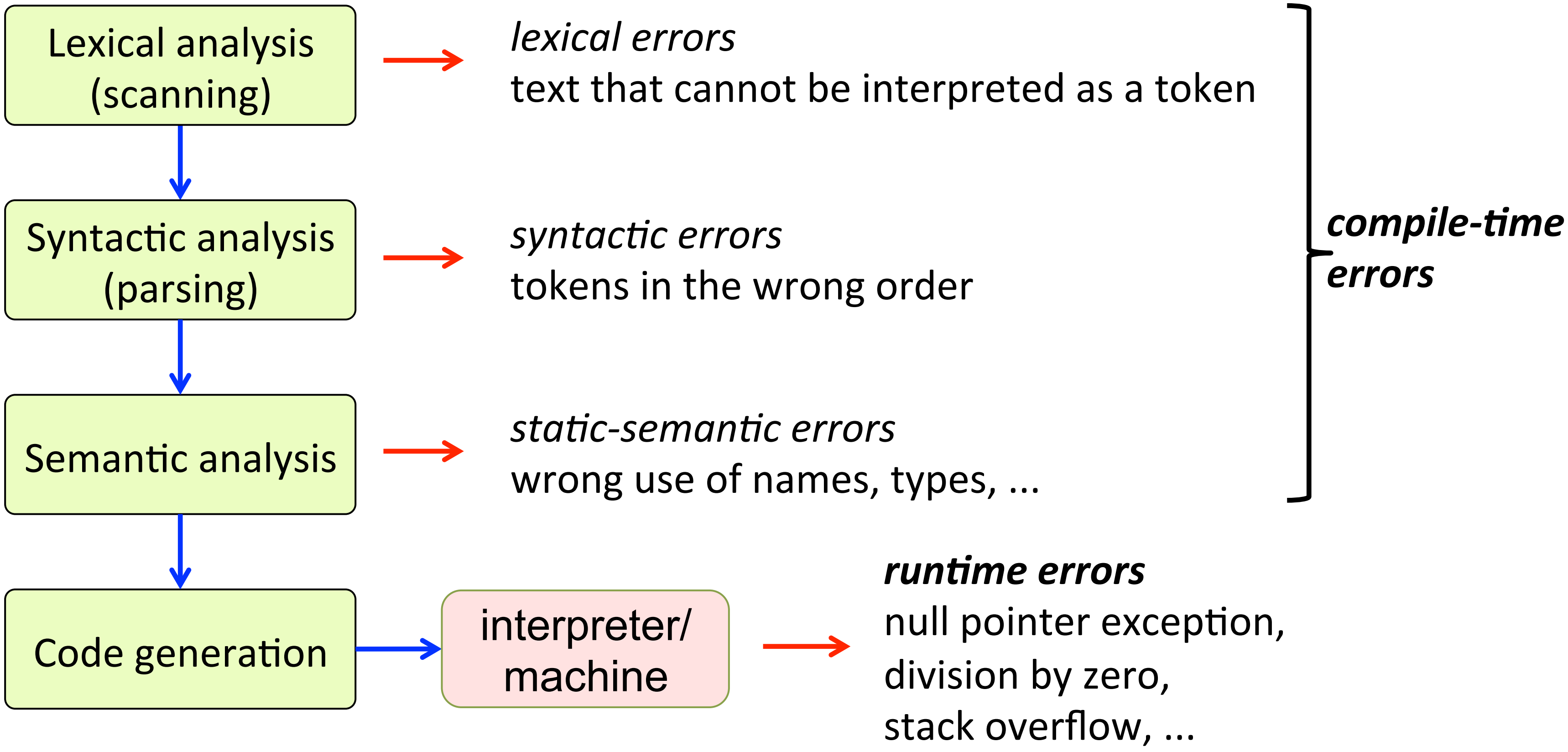



See the course Optimizing Compilers, EDA230

# Generating the compiler:



# Program errors




***logic errors***

Compute the wrong result.
Not caught by the compiler or the machine.
Normally try to catch using test cases.
Assertions and program verification can also help.

# Example errors

Lexical error:

```
int # square(int x) {
    return x * x;
}
```

Runtime error:

```
int p(int x) {
    return x / 0;
}
```

Syntactic error:

```
int double square(int x) {
    return x * x;
}
```

Logic error:

```
int square(int x) {
    return 2 * x;
}
```

Static-semantic error:

```
boolean square(int x) {
    return x * x;
}
```

# Safe versus unsafe languages

- **Safe language**

  All runtime errors are caught by the generated code and/or runtime system, and are reported in terms of the language.

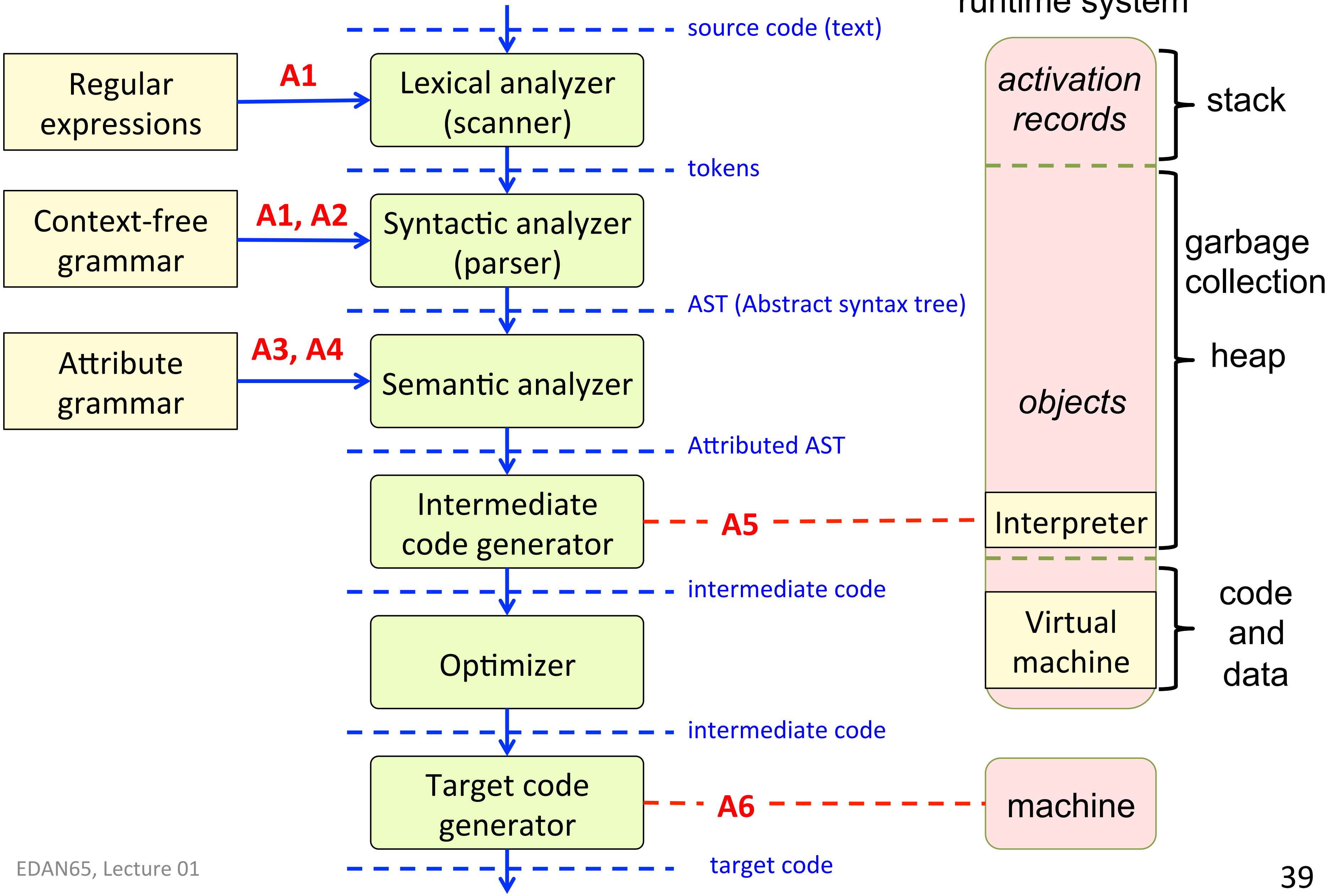
  Examples: Java, C#, Smalltalk, Python, ...

- **Unsafe language**

  Runtime errors in the generated code can lead to undefined behavior, for example an out of bounds array access. In the best case, this gives a hardware exception soon after the real error, stopping the program ("segmentation fault"). In the worst case, the execution continues, computing the wrong result or giving a segmentation fault much later, leading to bugs that can be extremely hard to find.

  Examples: C, Assembly

# Course overview



# After this course...

- You will have built a complete compiler
- You will have seen new declarative ways of programming
- You will have learnt some fundamental computer science theory
- You will have experience from using several practical tools
- You might be interested in doing a compiler project in the EDAN70 course (Project in Computer Science)
- You might be interested in doing a master's thesis project in compilers (related to research or industry)

# Applications of compiler construction

- Traditional compilers from source to assembly
- Source-to-source translators, preprocessors
- Interpreters and virtual machines
- Integrated programming environments
- Analysis tools
- Refactoring tools
- Domain-specific languages

# Examples of Domain-Specific Languages

# HTML

```
...
<h3>Lecture 1: Introduction. Mon 13-15. <a href="http://
fileadmin.cs.lth.se/cs/Education/EDAN65/2016/documents/
EDAN65-map.pdf">M:A</a></h3>
  <ul>
    <li><a href="http://fileadmin.cs.lth.se/cs/Education/
EDAN65/2016/lectures/L01.pdf">Slides</a>
    <li>Appel Book: Ch 1-1.2
    <li><a href ="https://moodle2.cs.lth.se/moodle/mod/quiz/
view.php?id=43">Moodle Quiz</a>
  </ul>
...
```

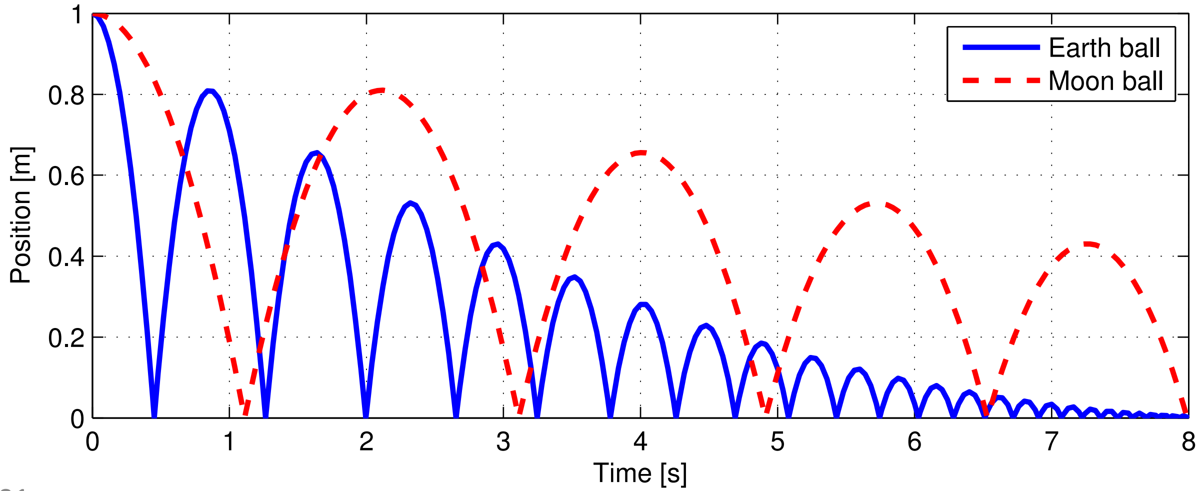
# .gitconfig

```
[user]
	name = Görel Hedin
	email = gorel.hedin@cs.lth.se
[push]
	default = simple
```

# Modelica

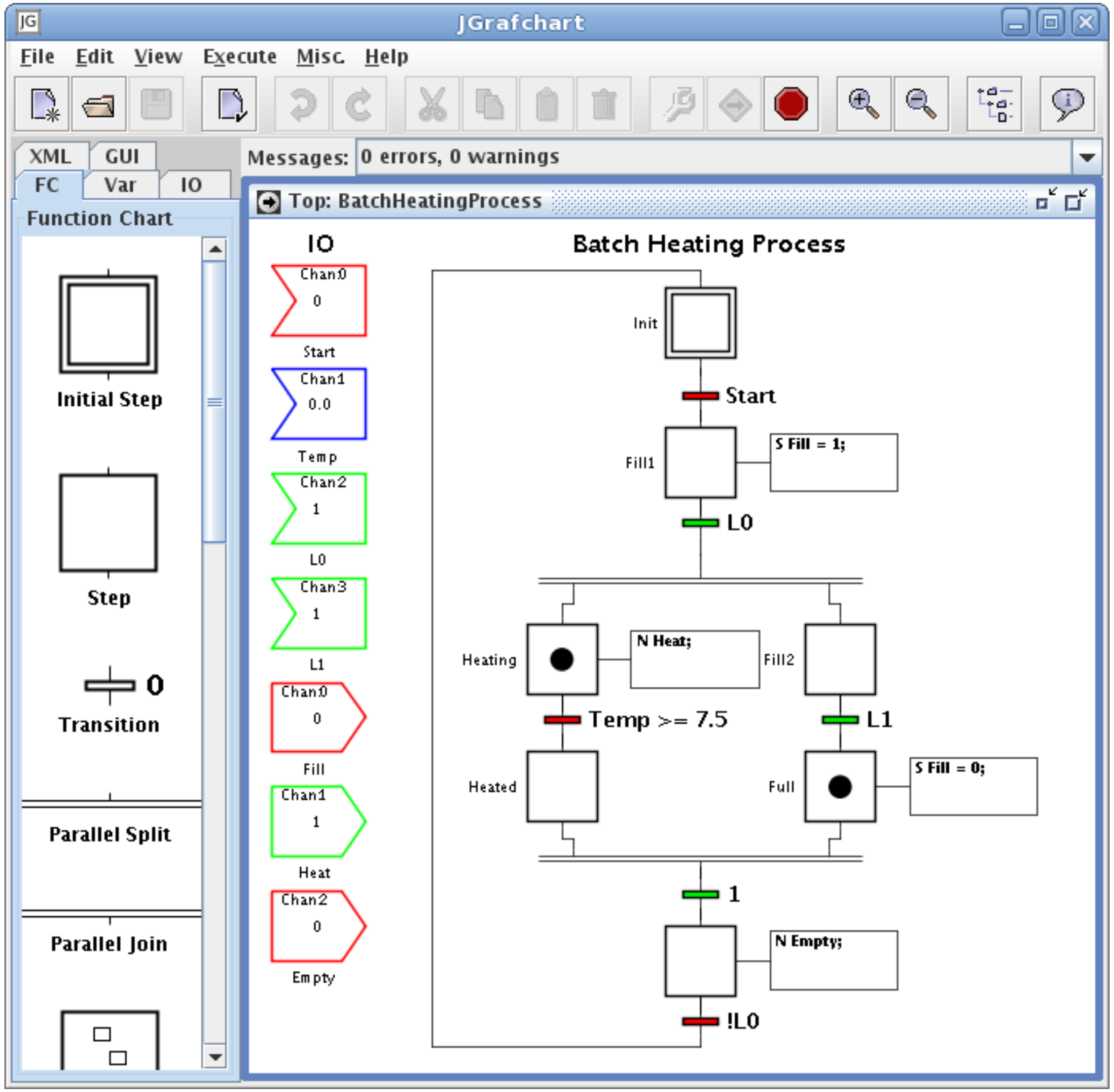
http://www.modelica.org

```
model BouncingBall //A model of a bouncing ball
  parameter Real g = 9.81; // Acceleration due to gravity
  parameter Real e = 0.9; // Elasticity coefficient
  Real pos(start=1); // Position of the ball
  Real vel(start=0); // Velocity of the ball
equation
  der(pos) = vel; / / Newtons second law
  der(vel) = -g;
  when pos <=0 then
    reinit(vel,-e*pre(vel)); // set velocity after bounce end when;
end BouncingBall;
```



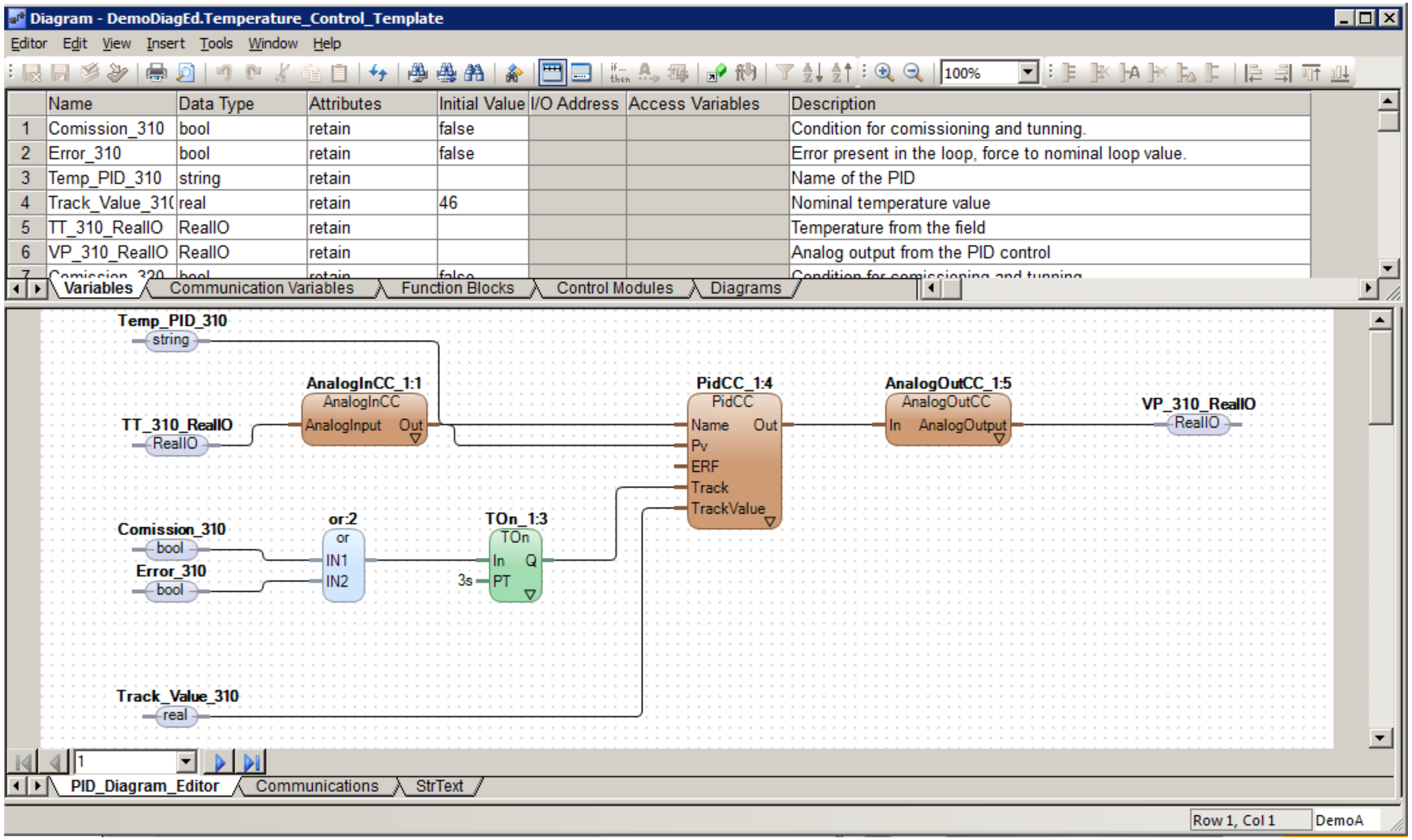
# Grafchart

http://www.control.lth.se/Research/tools/grafchart.html



# Control Builder Diagram

http://new.abb.com



# Related research at LTH

- Extensible compiler tools (Görel Hedin)
- Real-time garbage collection (Roger Henriksson)
- Code optimization for multiprocessors (Jonas Skeppstedt)
- Natural language processing (Pierre Nugues)
- Constraint solver languages (Krzysztof Kuchcinski)
- Data-flow languages (Jörn Janneck)
- Languages for pervasive systems (Boris Magnusson)
- Languages for requirements modeling (Björn Regnell)
- Languages for simulation and control (The control department)

# Summary questions

- What are the major compiler phases?
- What is the difference between the analysis and synthesis phases?
- Why do we use intermediate code?
- What is the advantage of separating the front and back ends?
- What is
  - a lexeme?
  - a token?
  - a parse tree?
  - an abstract syntax tree?
  - intermediate code?
- What is the difference between assembly code, object code, and executable code?
- What is bytecode, an interpreter, a virtual machine?
- What is a JIT compiler?
- What kind of errors can be caught by a compiler? A runtime system?

See [http://cs.lth.se/edan65/week-by-week](http://cs.lth.se/edan65/week-by-week) for what to do this week.