EDAN65: Compilers

Introduction and Overview

Görel Hedin

Revised: 2015-08-31

Course registration

- Confirm by signing the Registration Form

- Prerequisites
  - Object-oriented programming and Java
  - Algorithms and data structures (recursion, trees, lists, hash tables, …)

CEQ

- Student representatives?

Course information

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

- 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), see web page.

Course structure

- 14 lectures, Mon 13-15, Tue 13-15, 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 15-17, Fri 08-10, or Fri 13-15. **Sign up by Thursday Sept 3**
  - Lab sessions start next week (but start this week on your work)
  - Assignments prerequisite for doing exam
- Lecture quizzes
  - New course feature. Do on your own.
- Exercises
  - Recommended exercises on the course web. Do on your own.
- Written exam, Tuesday Oct 27, 2015
  - Re-exam, Friday Jan 8, 2016 (sign up by Dec 16)

Instructors

- Lectures
  - Prof. Görel Hedin
- Programming assignments and lab sessions
  - Ph. D. student Niklas Fors
  - Ph. D. student Jesper Öqvist
  - Researcher Christoff Bürger

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:

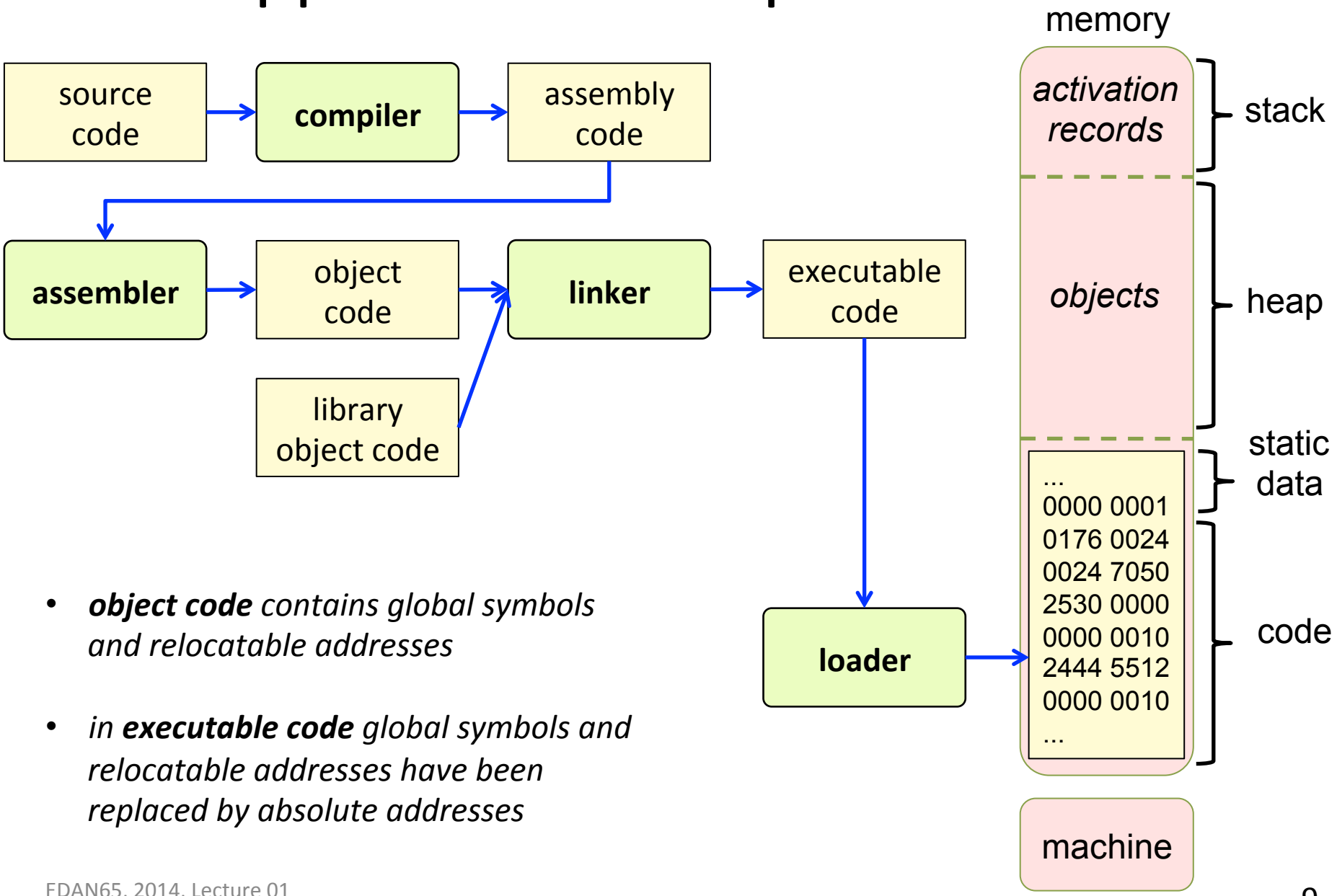
```
...
csum = a + b + 1;
...
```

compiler

```
        .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?

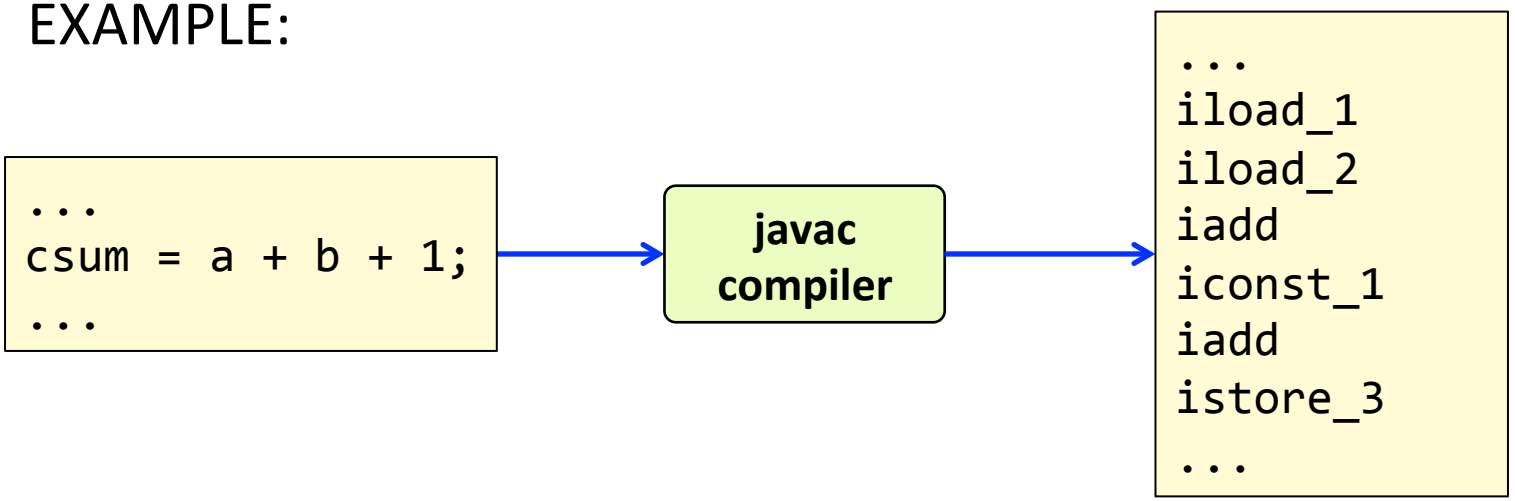


- ***object code*** *contains global symbols and relocatable addresses*
- *in* ***executable code*** *global symbols and relocatable addresses have been replaced by absolute addresses*

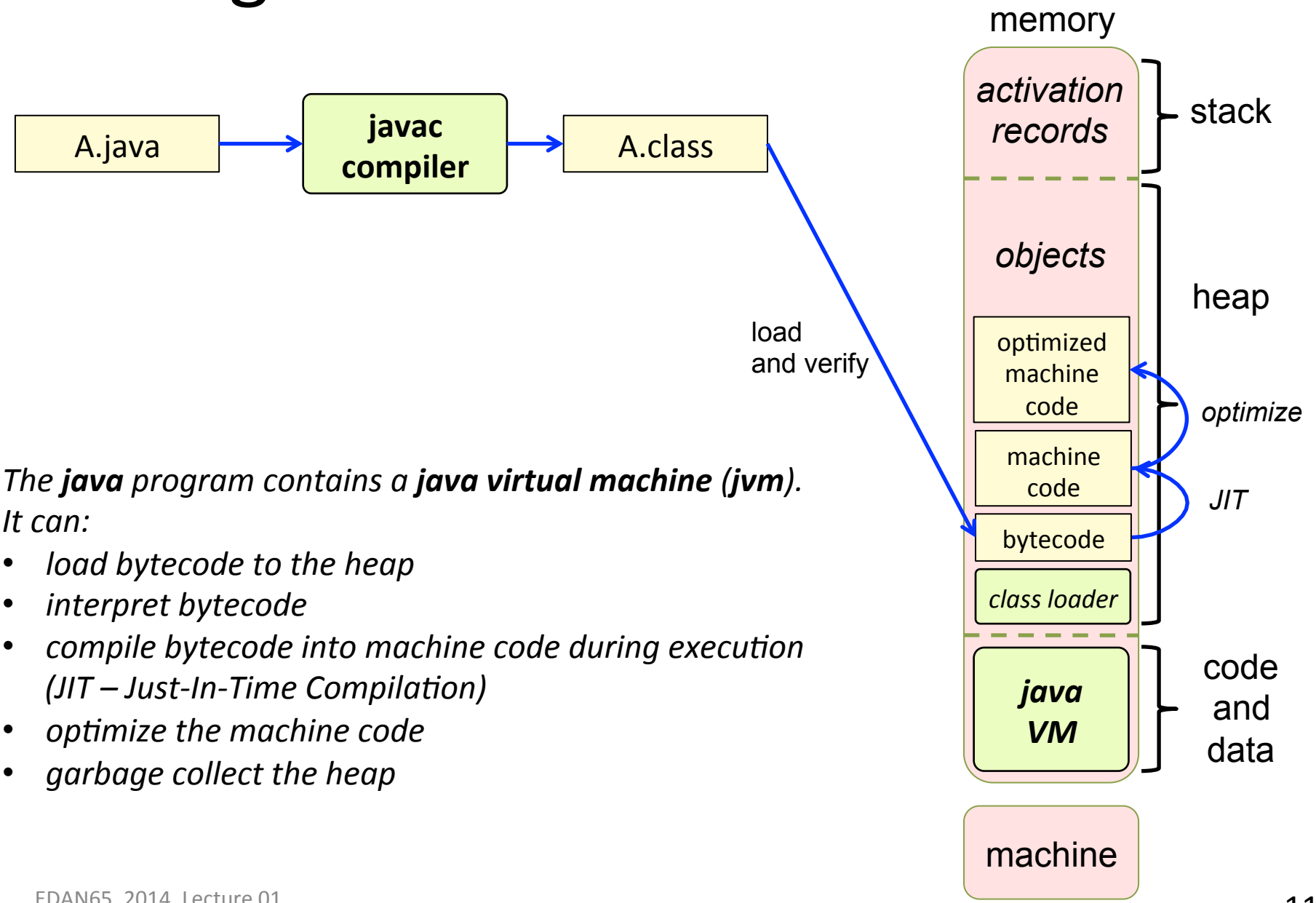
What about Java?

class file
(java bytecode)

EXAMPLE:



Running Java code?

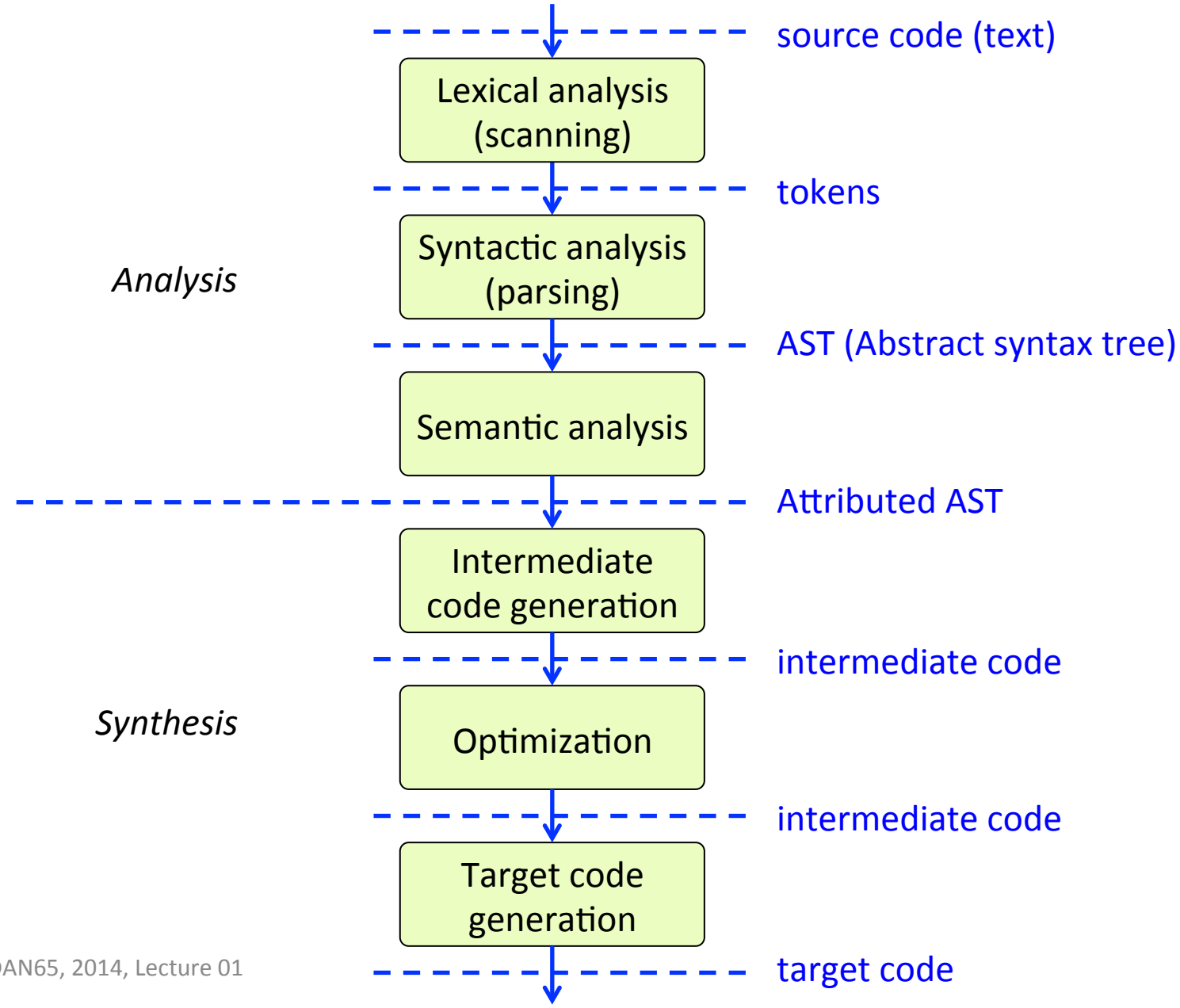


*The **java** program contains a **java virtual machine (jvm)**. It can:*

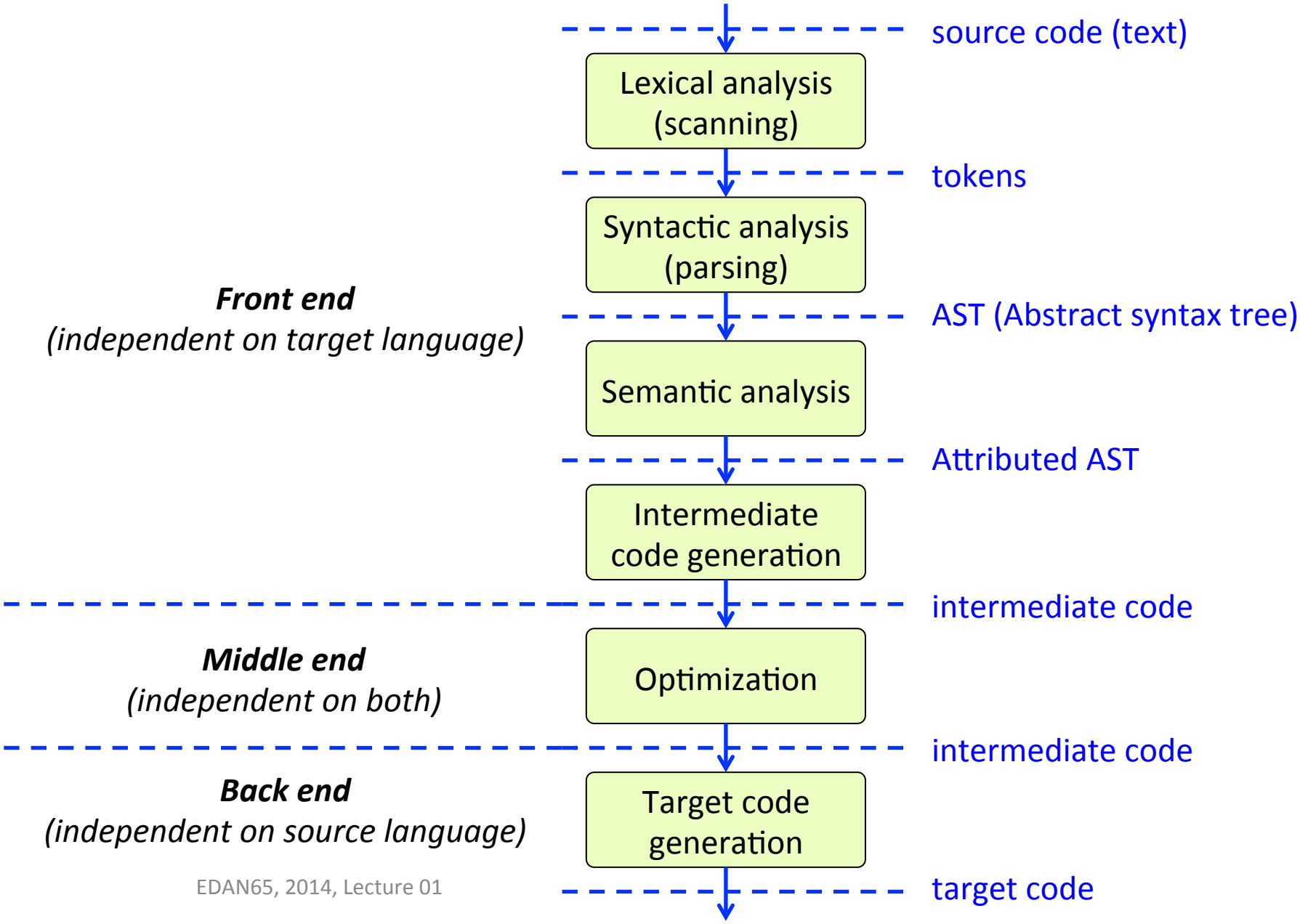
- *load bytecode to the heap*
- *interpret bytecode*
- *compile bytecode into machine code during execution (JIT – Just-In-Time Compilation)*
- *optimize the machine code*
- *garbage collect the heap*

Inside the compiler:

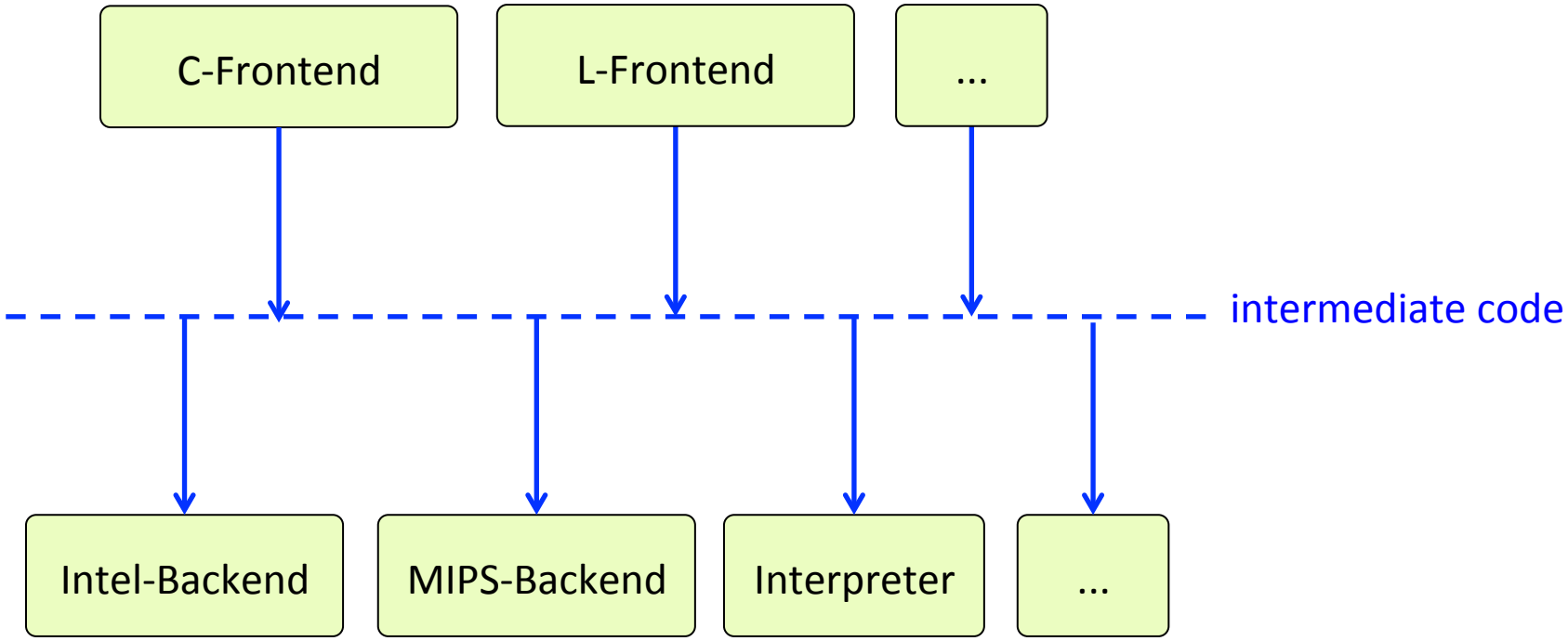
Each ***phase*** converts the program from one ***representation*** to another



Front and back end:



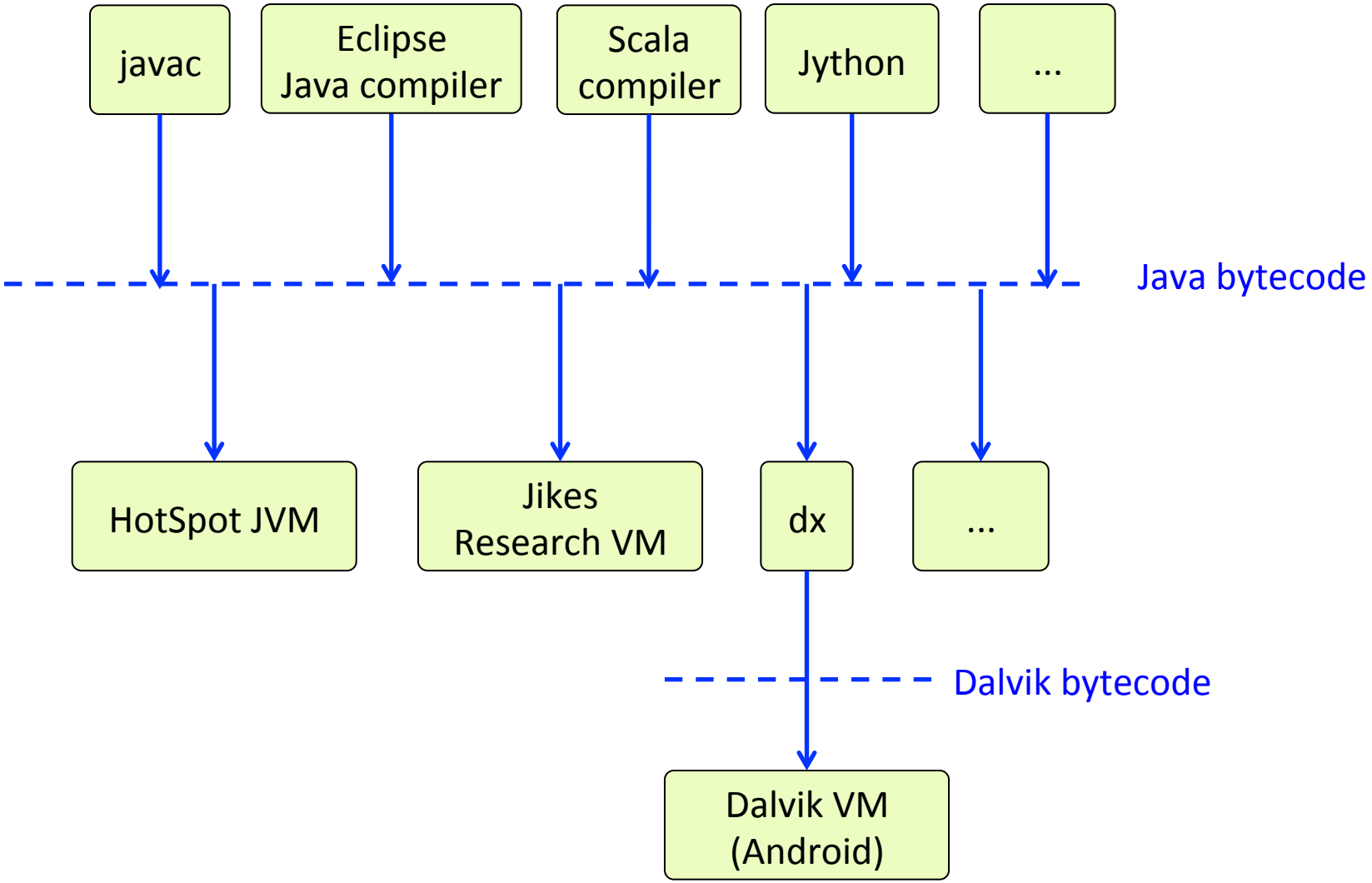
Several front and back ends:



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)

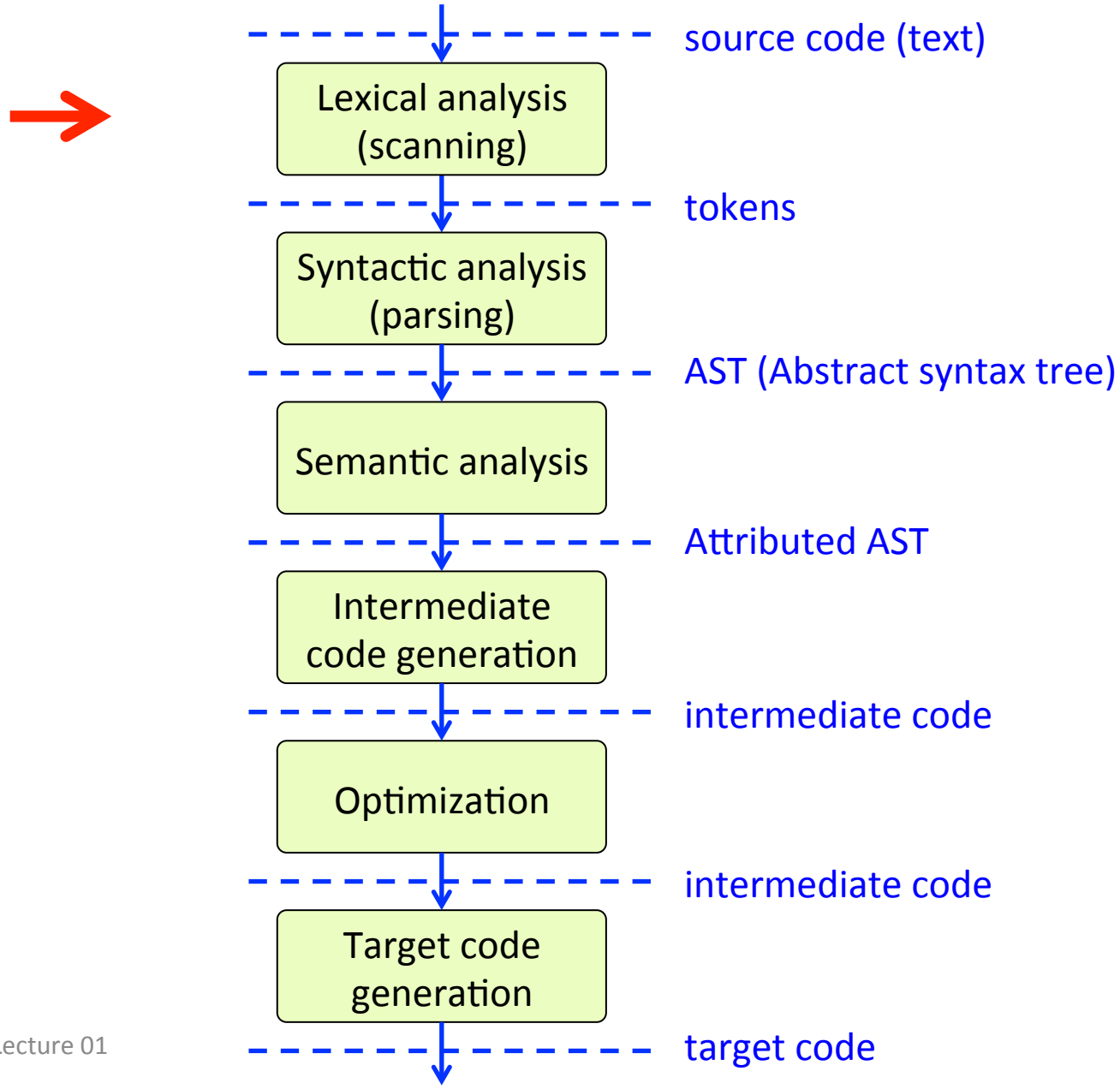
Some terminology

- 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

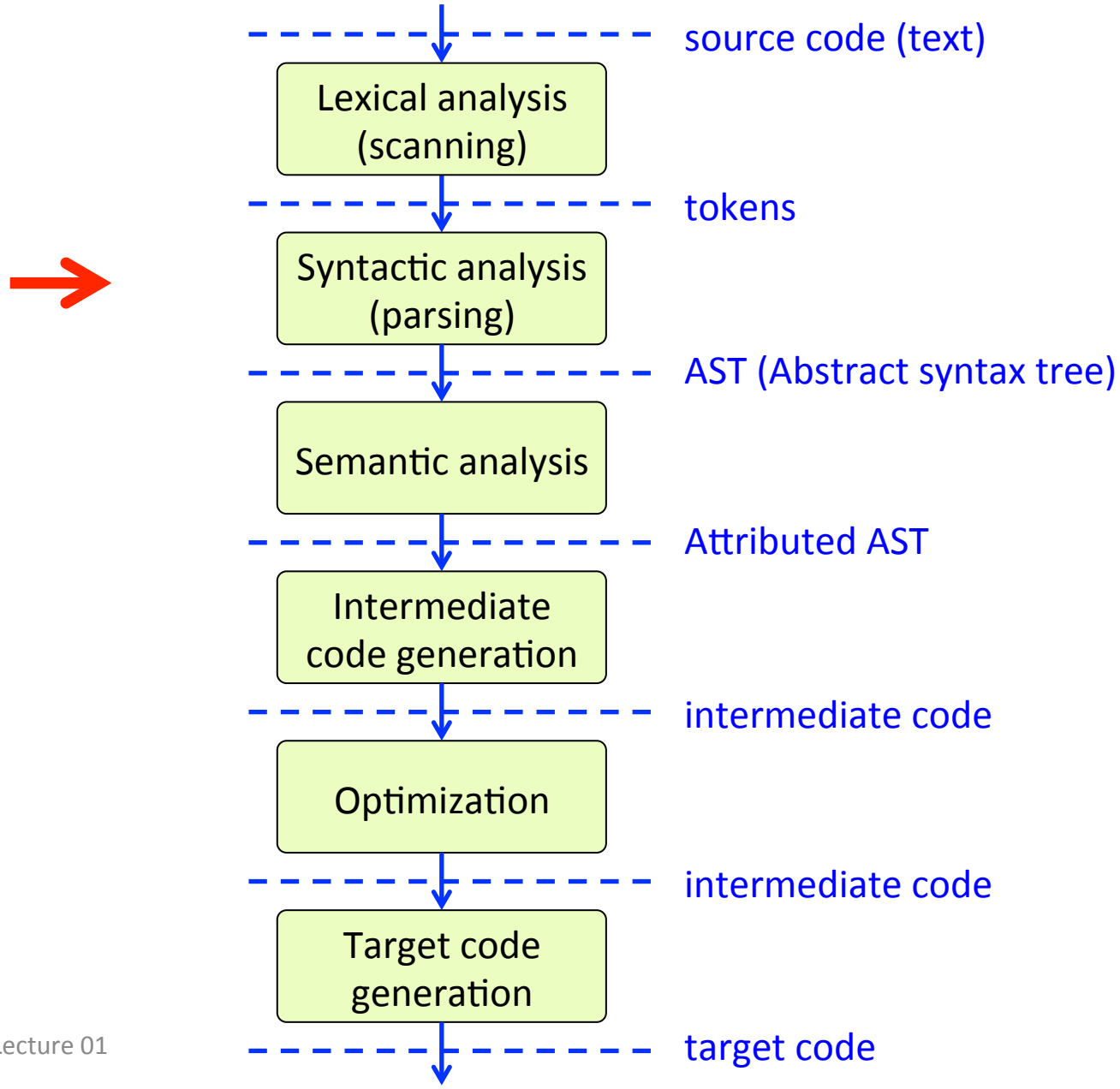
```
while (k<=n) {
  sum=sum+k;
  k=k+1;
}
```

Tokens

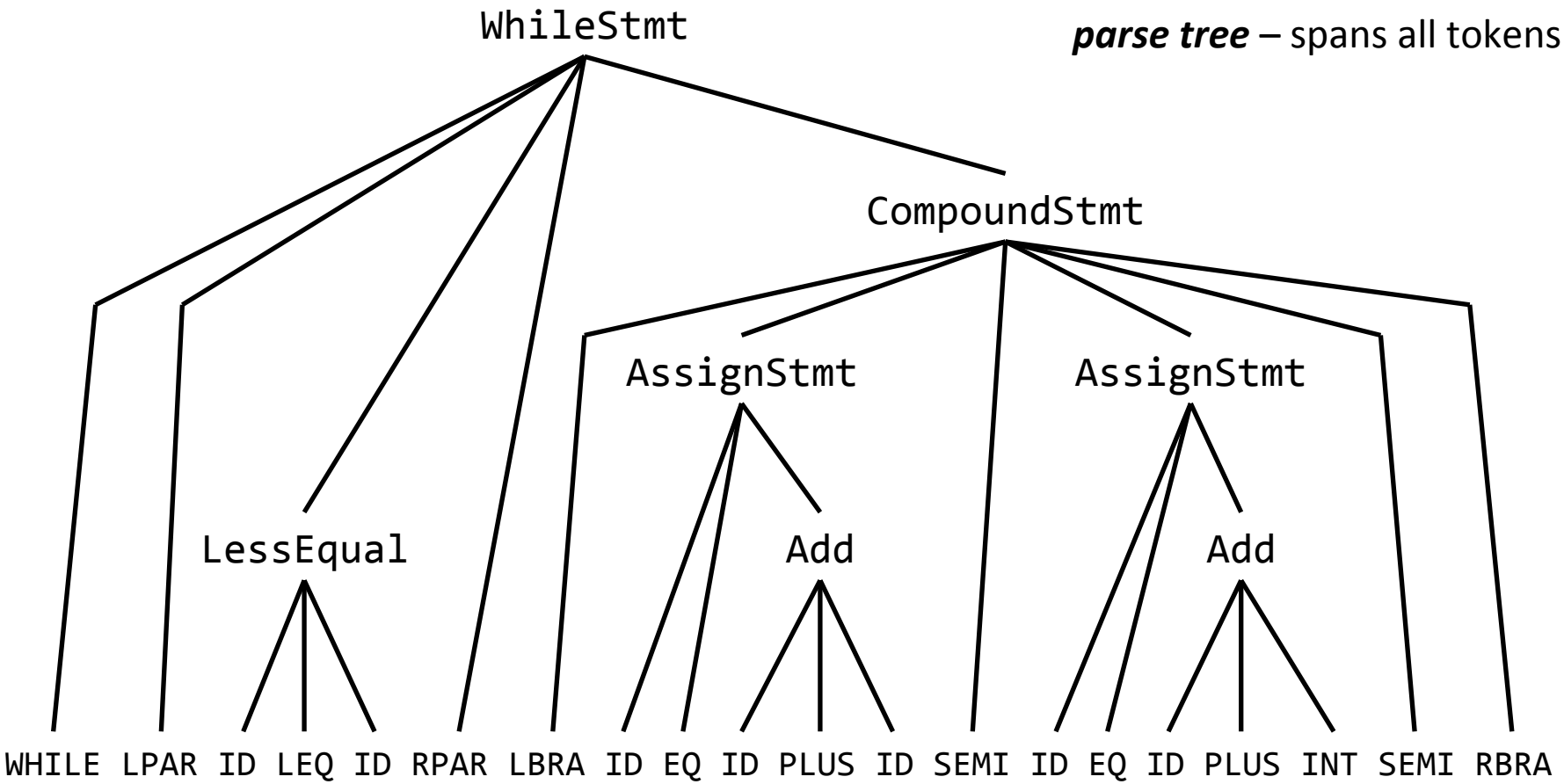
```
WHILE LPAR ID(k) LEQ ID(n) RPAR LBRA
ID(sum) EQ ID(sum) PLUS ID(k) SEMI
ID(k) EQ ID(k) PLUS INT(1) SEMI
RBRA
```

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

Compiler phases and program representations:



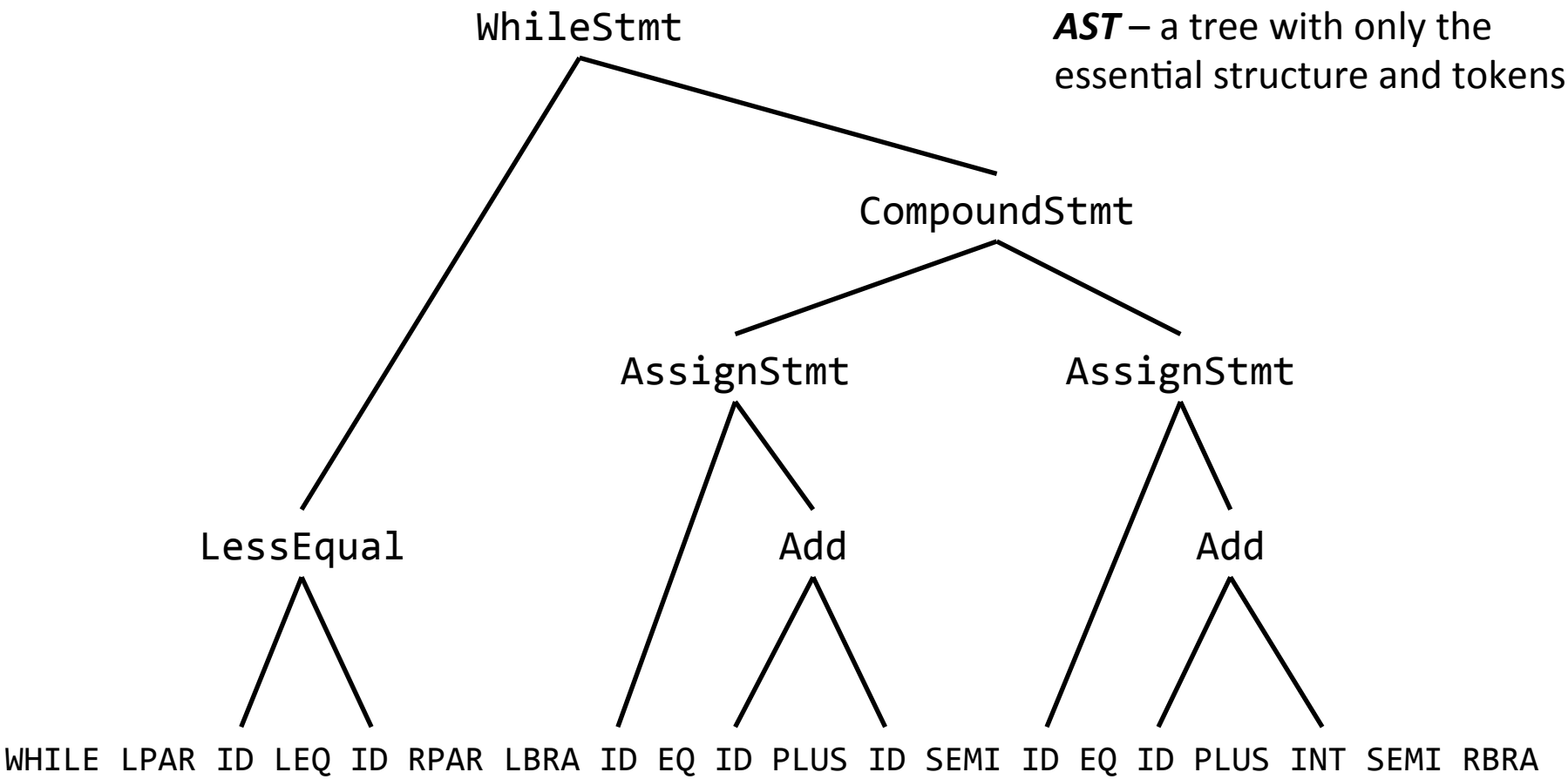
Syntactic analysis (parsing)



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 ; }
```

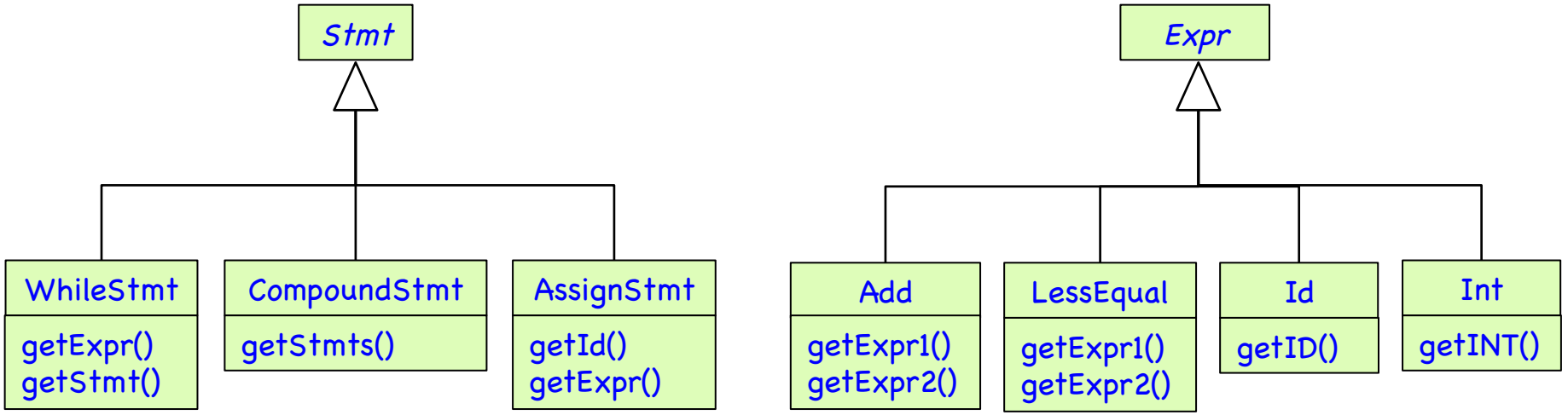
Abstract syntax trees

- 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 (statements, expressions, declarations, ...)
  - concrete classes (while, if, add, subtract, ...)

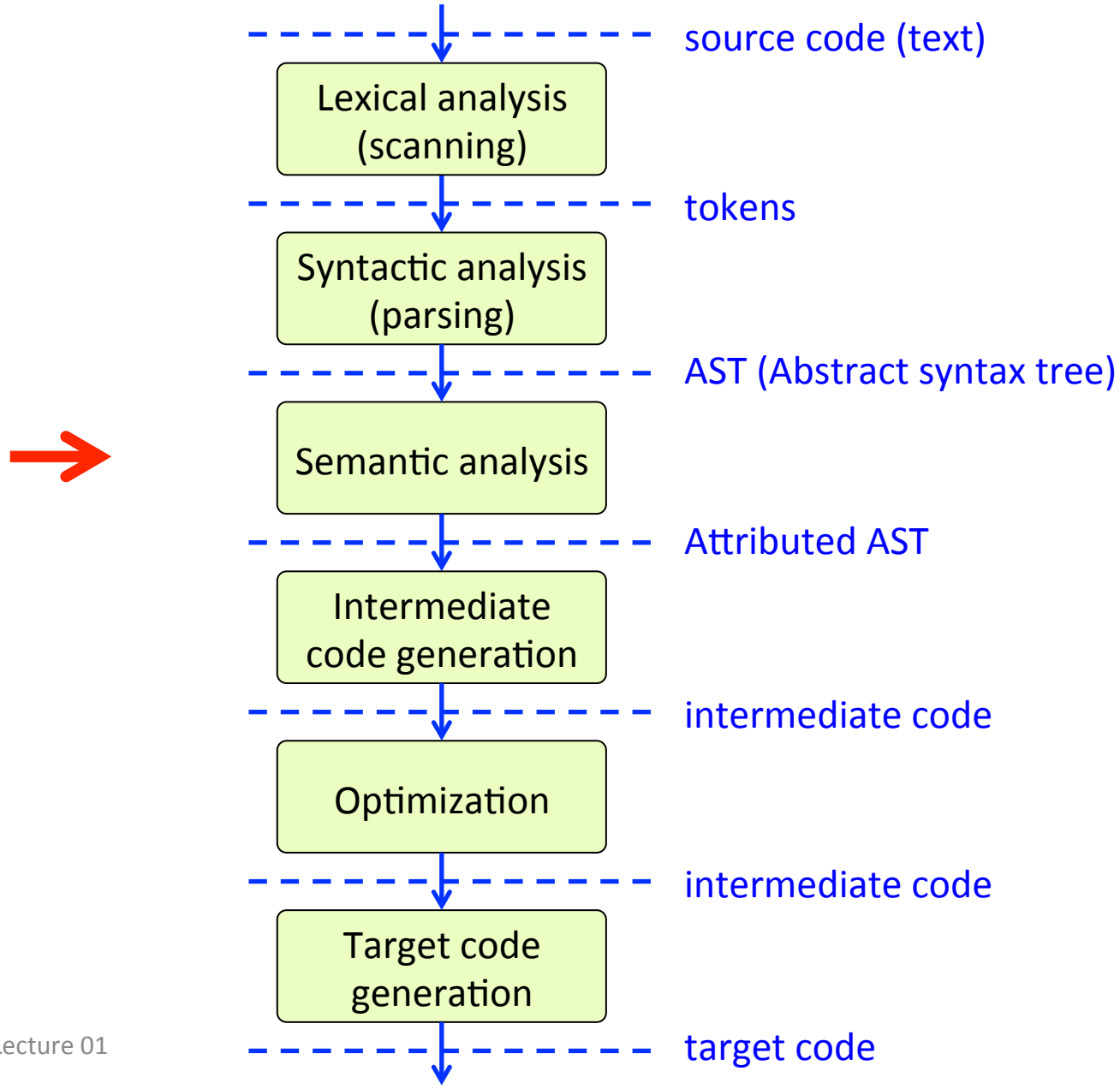
AST class hierarchy

- Create class hierarchies for statements and expressions!
- Invent names for suitable abstract classes!
- Add getters for traversing the AST!

AST class hierarchy



Compiler phases and program representations:



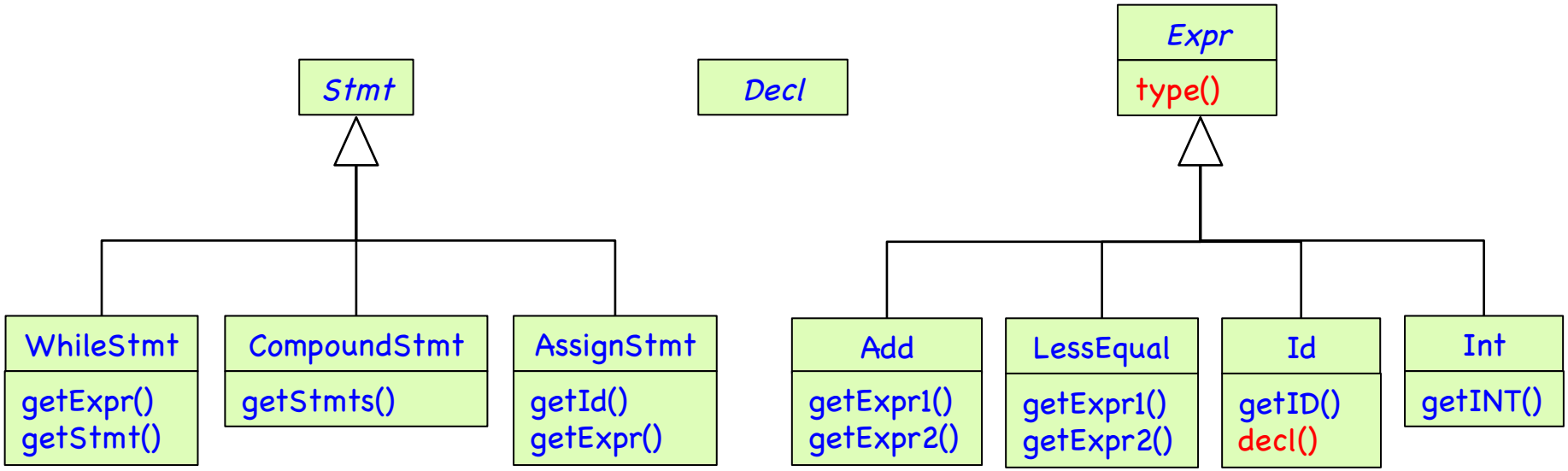
Semantic analysis

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?

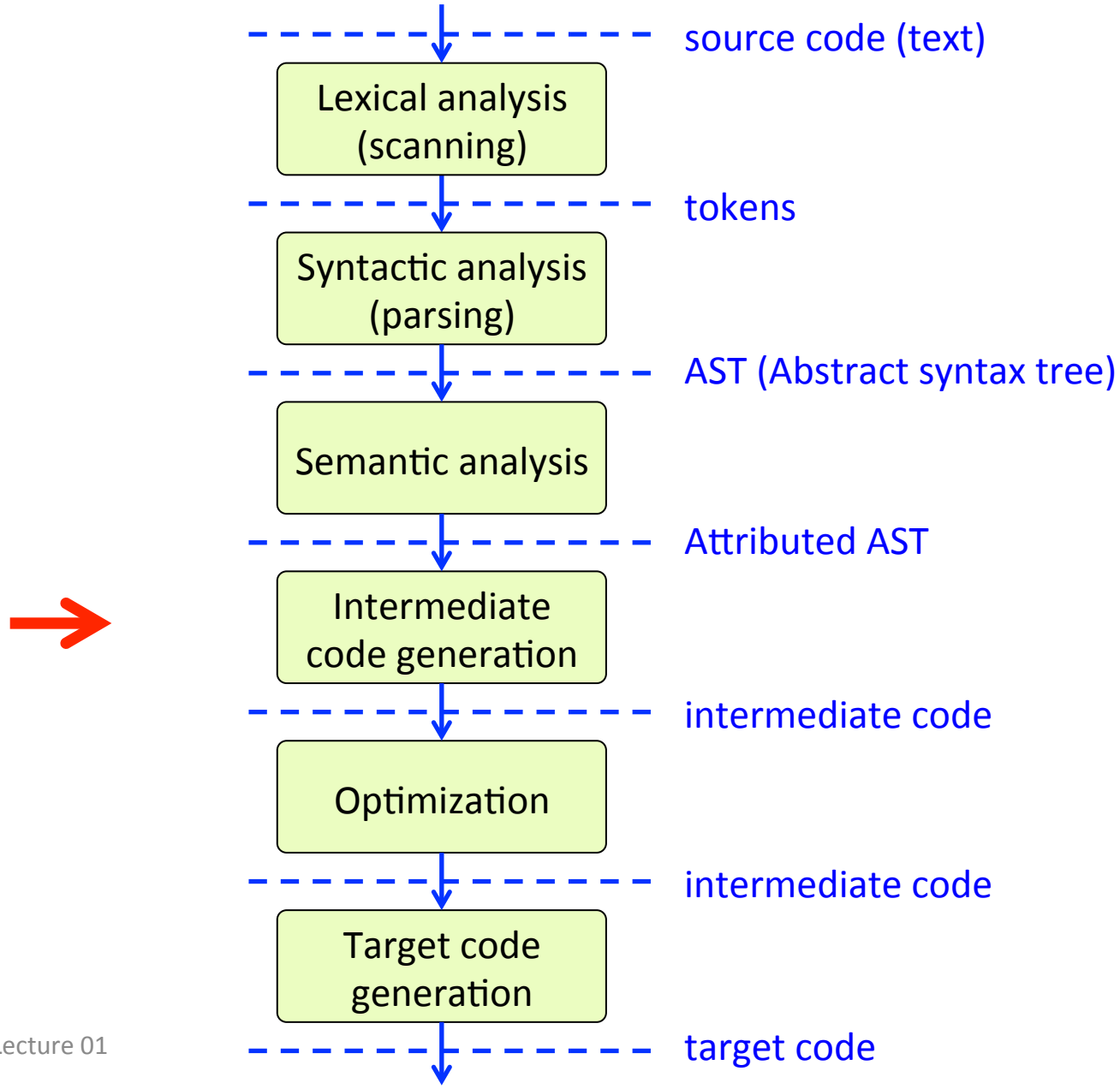
Analysis aided by adding *attributes* to the AST (properties of AST nodes)

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:



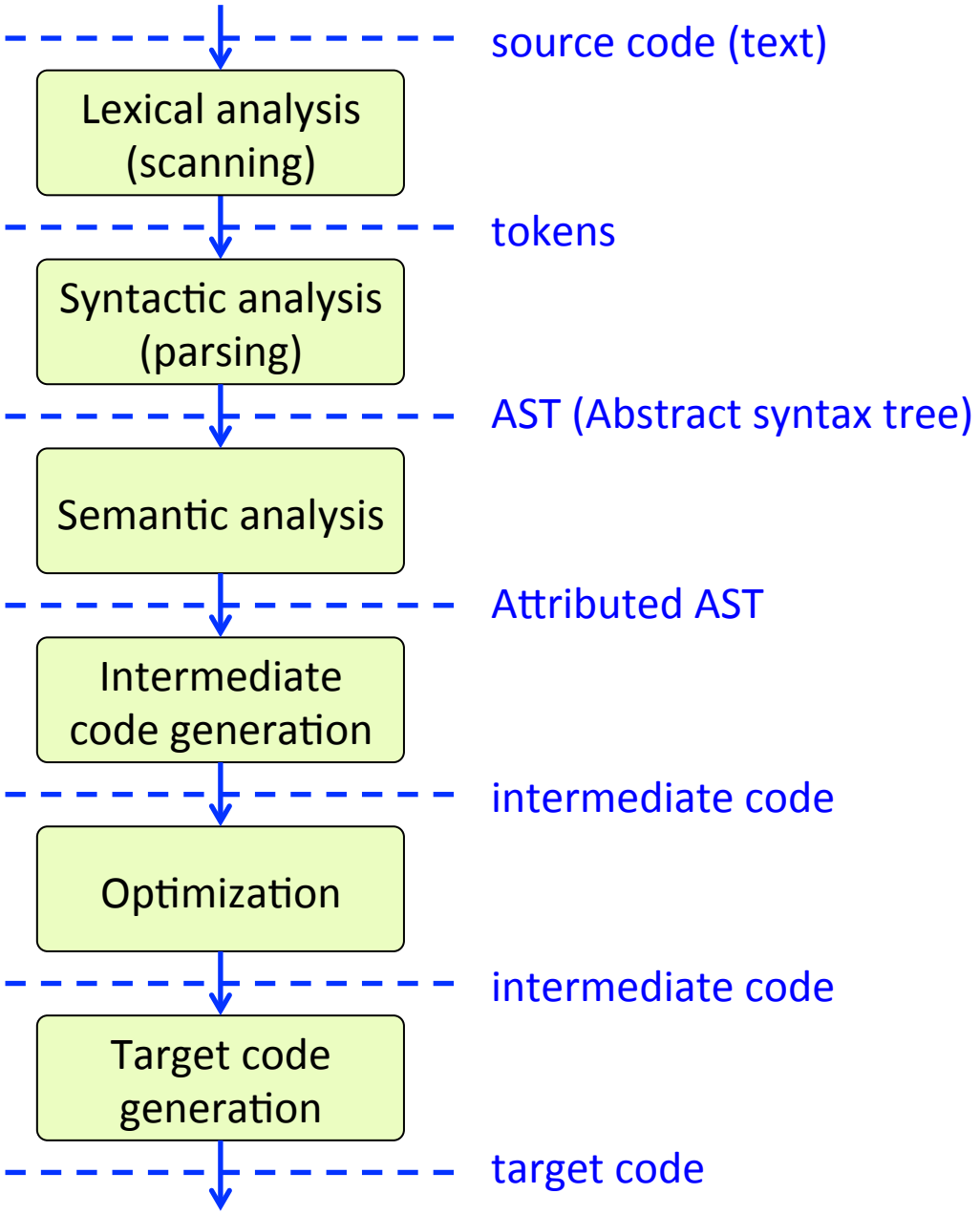
Intermediate code generation

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)

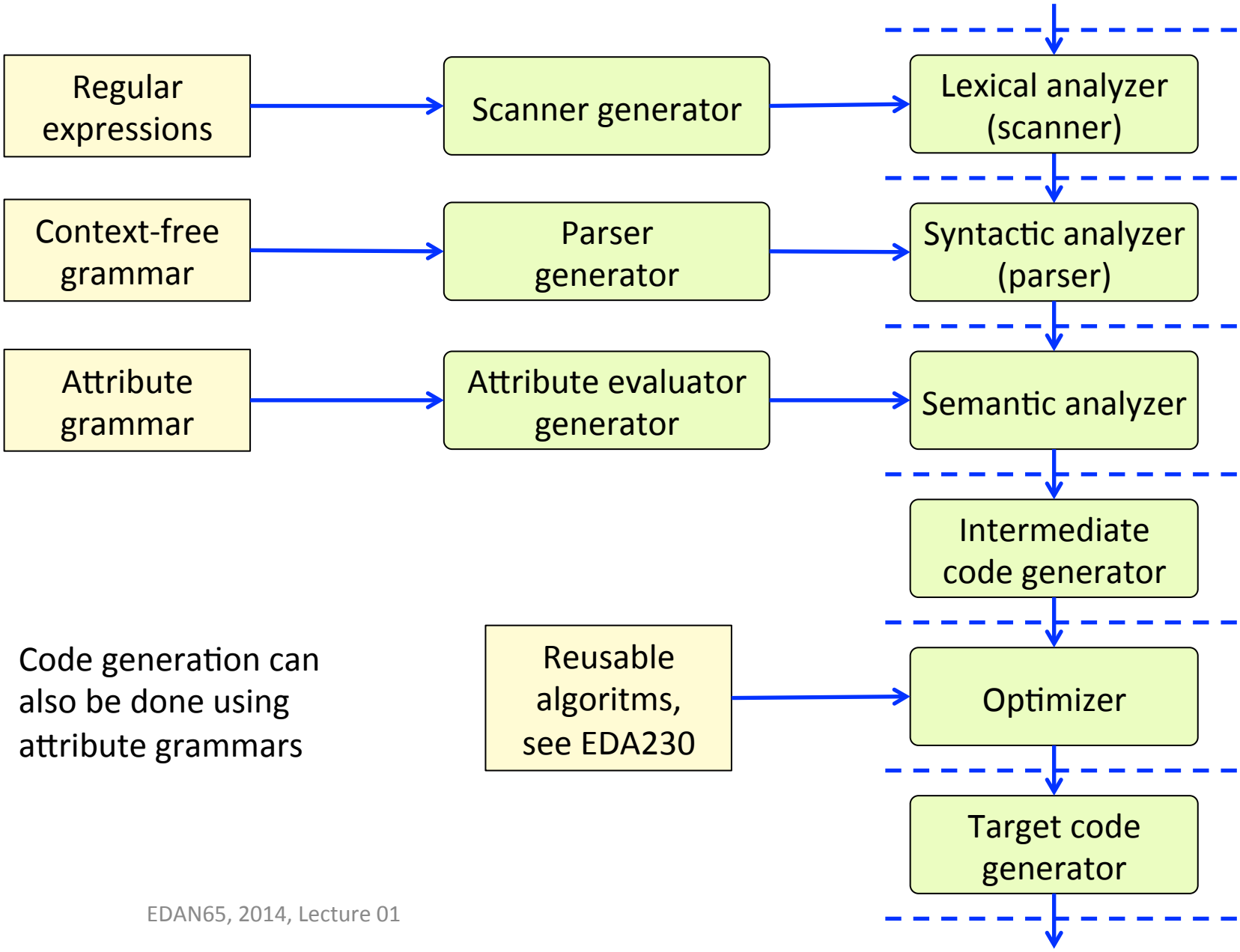
By adding suitable attributes to the AST, code generation becomes simple.

Compiler phases and program representations:



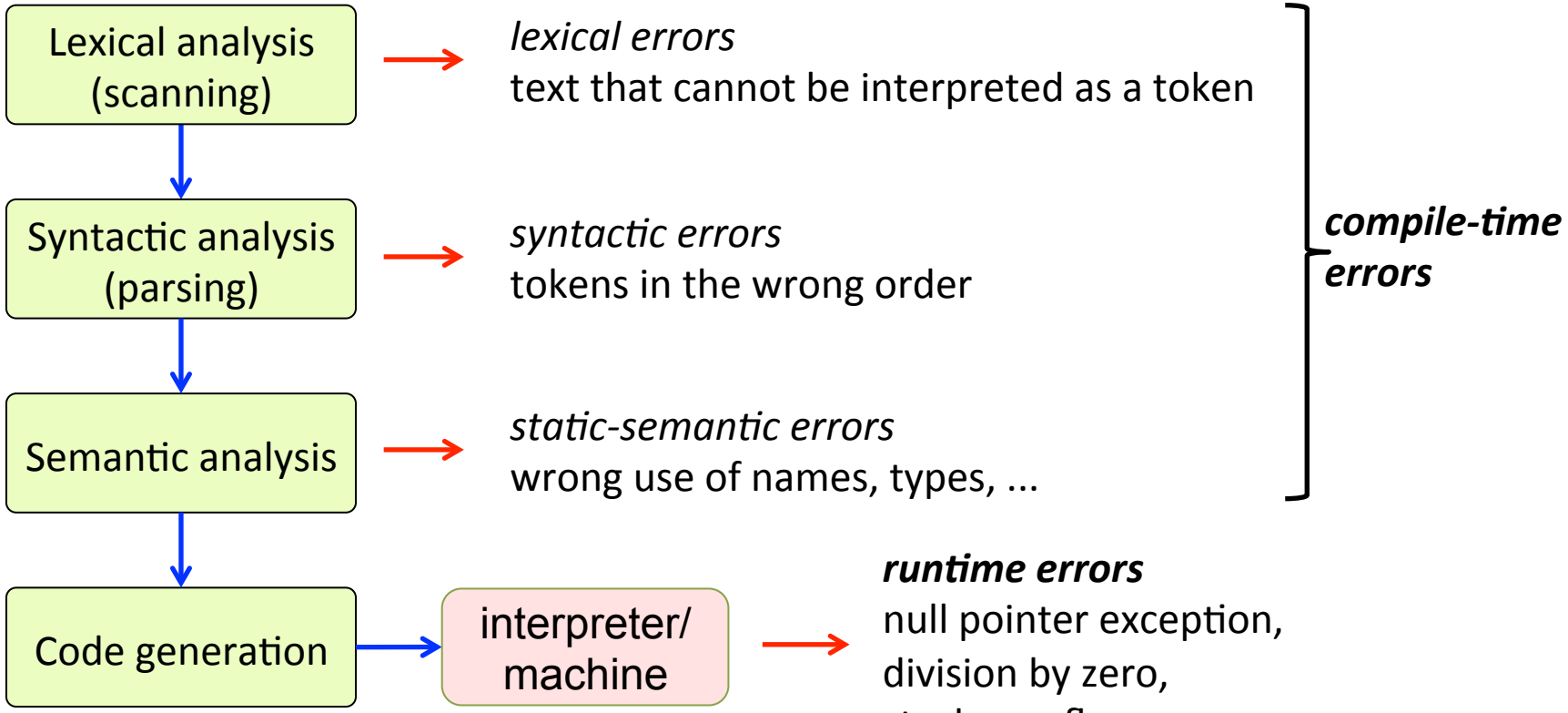
See the course Optimizing Compilers, EDA230

Generating the compiler:



Code generation can also be done using attribute grammars

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 square(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.

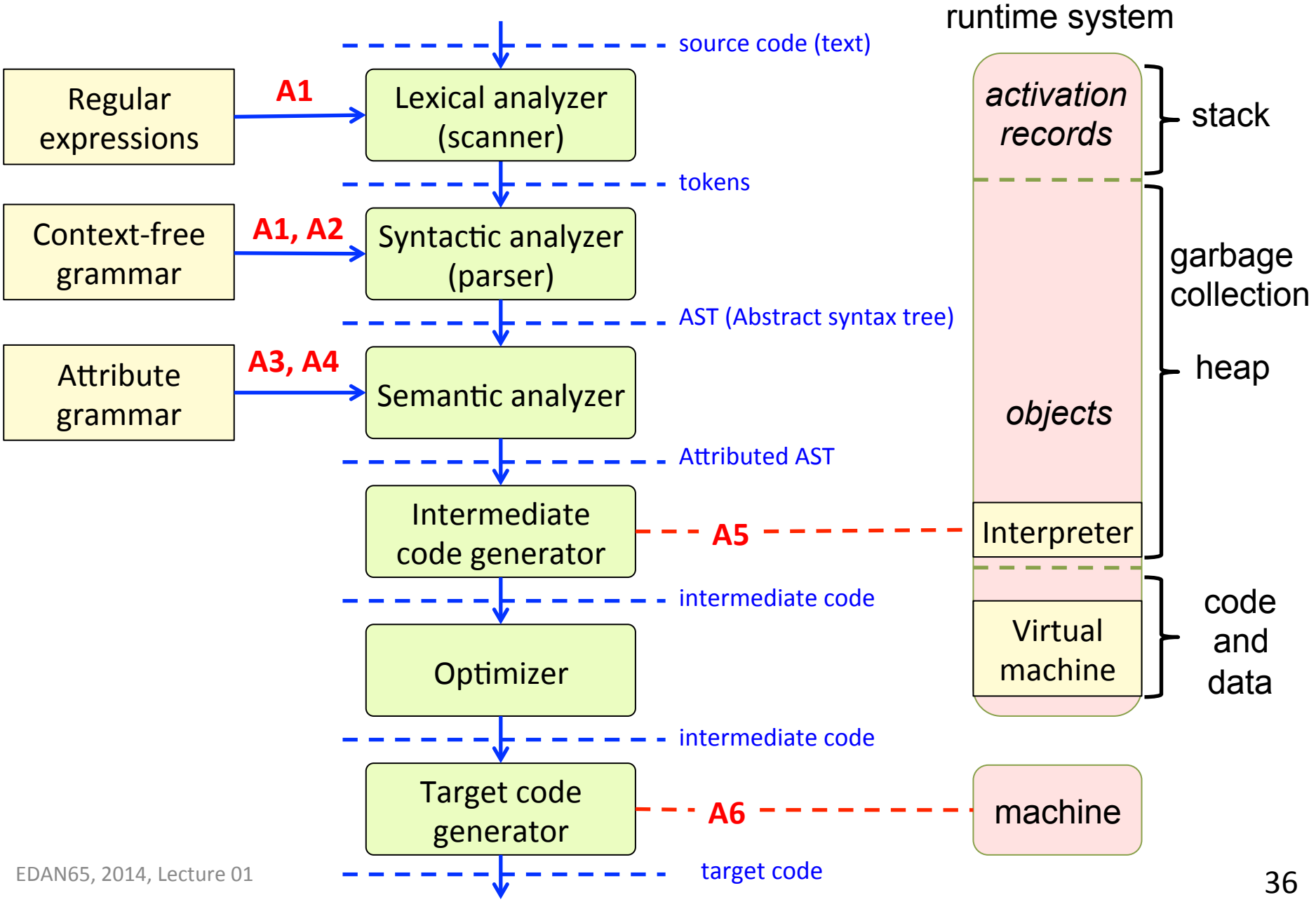
  Examples: Java, C#, Smalltalk, Python, ...

- **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/EDAN65/2015/documents/
EDAN65-map.pdf">DC: Stora Hörsalen</a></h3>
  <ul>
    <li><a href="http://fileadmin.cs.lth.se/cs/Education/
EDAN65/2015/lectures/L01.pdf">Slides</a>
    <li>Appel Book: Ch 1-1.2
    <li><a href ="http://moodle.cs.lth.se/moodle/mod/quiz/
view.php?id=493">Moodle Quiz</a>
  </ul>
...
```

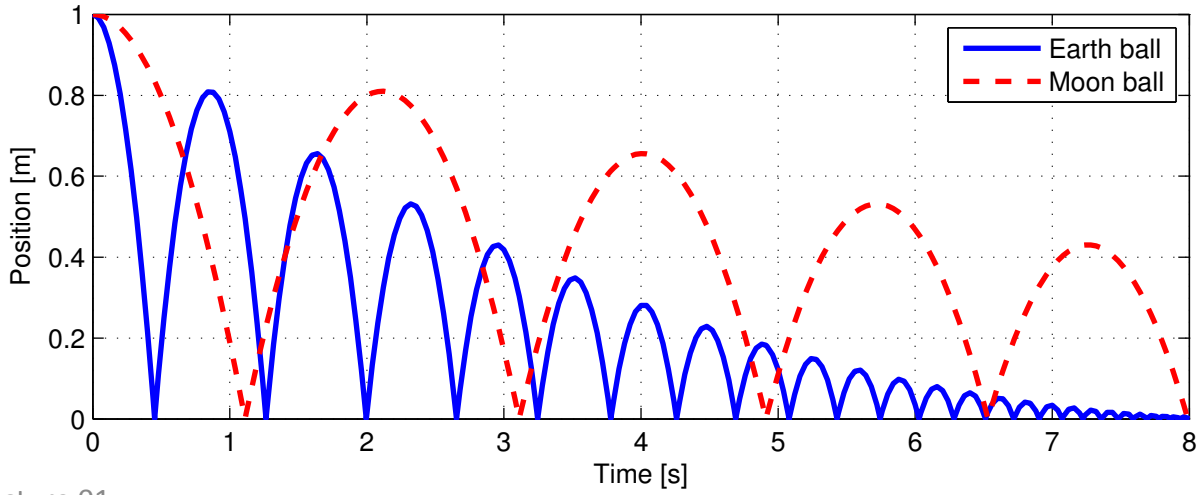
.gitconfig

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

Modelica

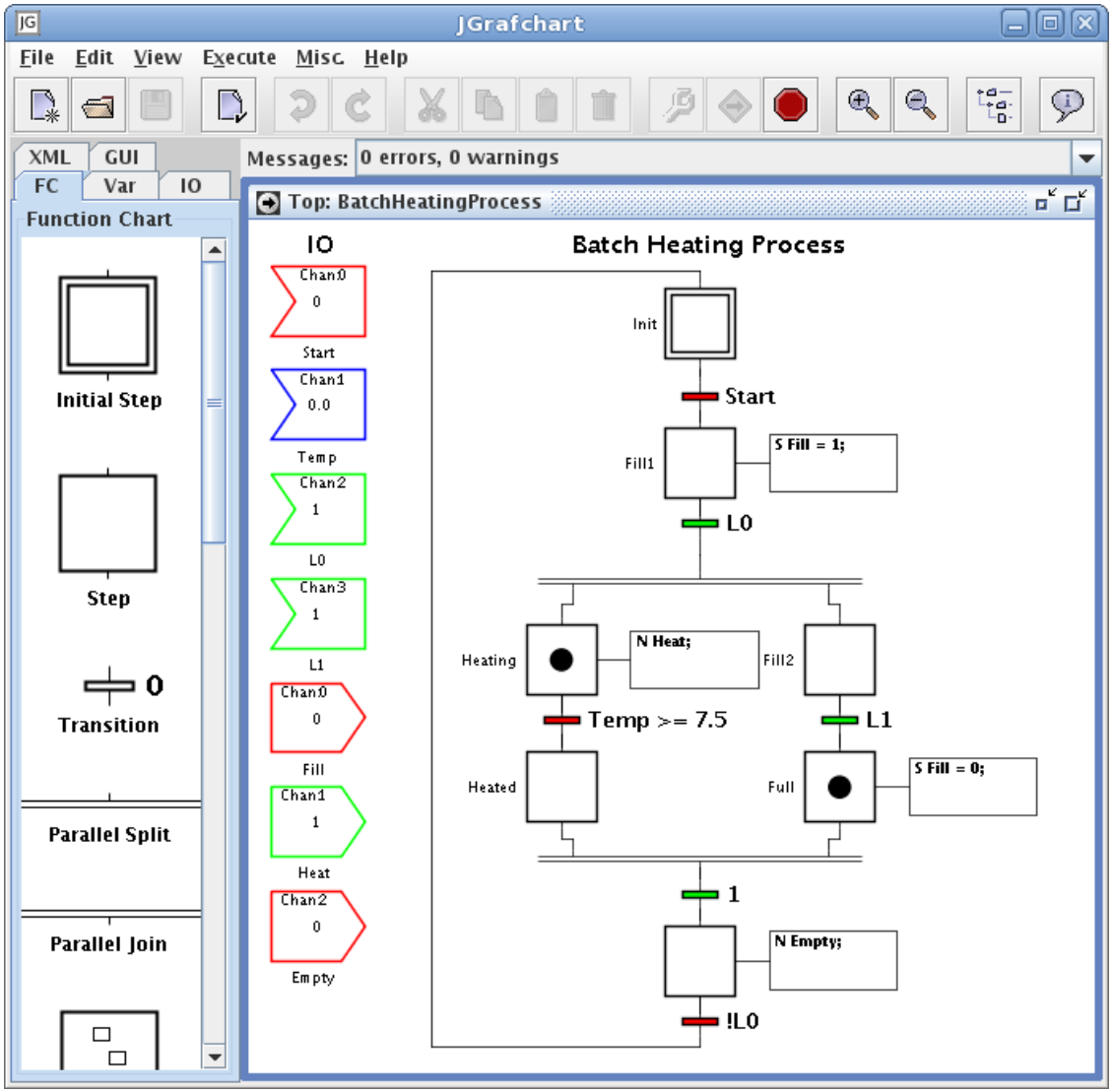
http://www.modelica.org

```
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;
```



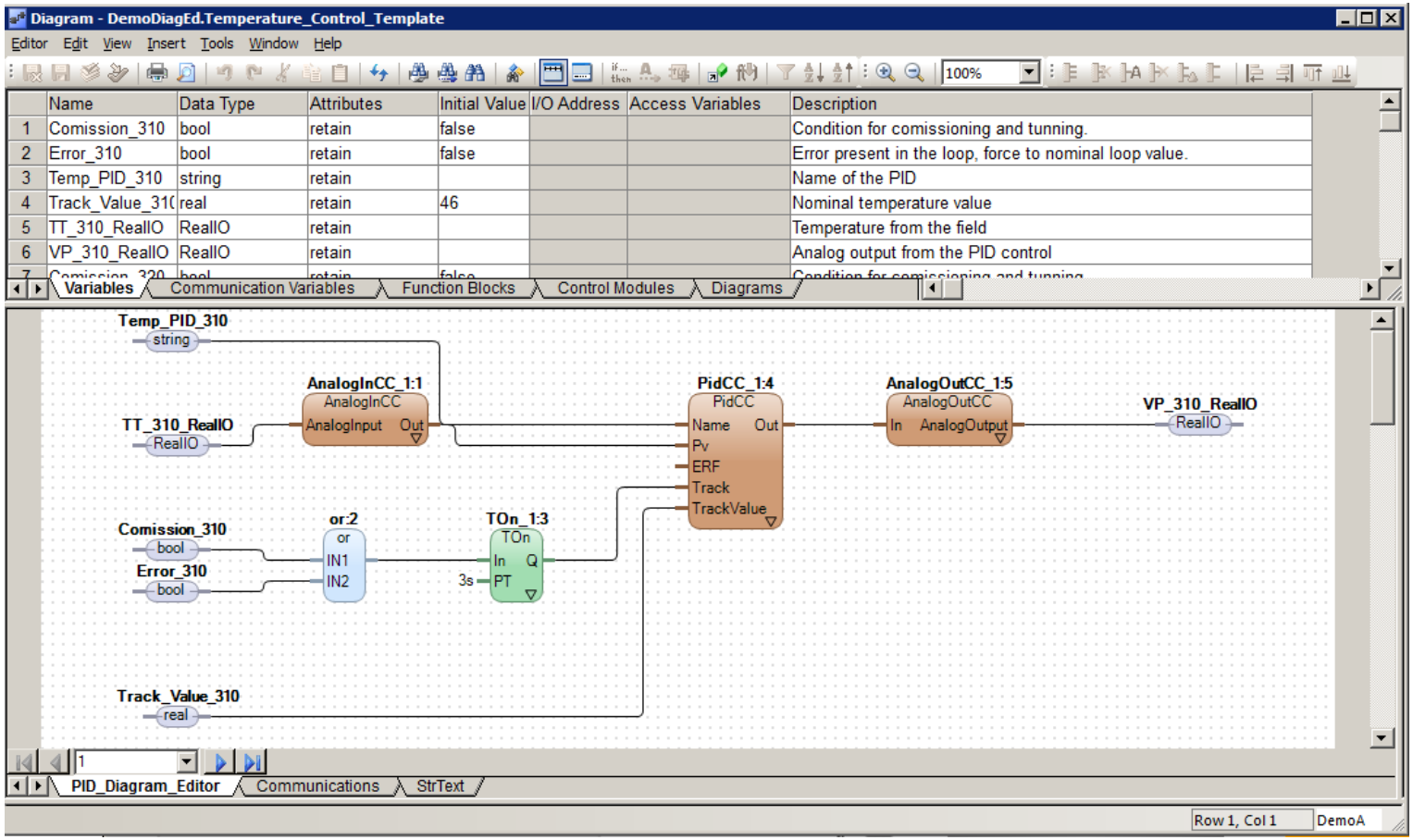
Grafchart

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 solvers (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?