PLaC-0.1

Programming Languages and Compilers

Prof. Dr. Uwe Kastens

WS 2013 / 2014

Lecture Programming Languages and Compilers WS 2013/14 / Slide 001

In the lecture:

Welcome to the lecture!

PLaC-0.2

0. Introduction

Objectives

The participants are taught to

- understand properties and notions of programming languages
- understand **fundamental techniques** of language implementation, and to use **generating tools and standard solutions**,
- apply compiler techniques for design and implementation of **specification languages and domain specific languages**

Forms of teaching:

Lectures

Tutorials

Exercises

Homeworks

Running project

Lecture Programming Languages and Compilers WS 2013/14 / Slide 002

Objectives:

Understand the objectives of the course.

In the lecture:

The objectives are explained.

Questions:

- What are your objectives?
- Do they match with these?
- When did you last listen to a talk given in English?

Contents

Lecture Programming Languages and Compilers WS 2013/14 / Slide 003

Objectives:

Overview over the topics of the course

In the lecture:

Comments on the topics.

Prerequisites

from Lecture	Topic	here needed for
Foundations of Programming Languages:		
	4 levels of language properties	Language specification, compiler tasks
	Context-free grammars	Grammar design, syntactic analysis
	Scope rules	Name analysis
	Data types	Type specification and analysis
Modeling:		
	Finite automata	Lexical analysis
	Context-free grammars	Grammar design, syntactic analysis

Lecture Programming Languages and Compilers WS 2013/14 / Slide 004

Objectives:

Identify concrete topics of other courses

In the lecture:

Point to material to be used for repetition

Suggested reading:

- Course material for *Foundations of Programming Languages*
- Course material for *Modeling*

Questions:

- Do you have the prerequisites?
- Are you going to learn or to repeat that material?

References

Material for this course **PLaC**: http://ag-kastens.upb.de/lehre/material/plac
for the Master course **Compilation Methods**: http://ag-kastens.upb.de/lehre/material/compii

Modellierung: http://ag-kastens.upb.de/lehre/material/model
Grundlagen der Programmiersprachen: http://ag-kastens.upb.de/lehre/material/gdp

John C. Mitchell: **Concepts in Programming Languages**, Cambridge University Press, 2003

R. W. Sebesta: **Concepts of Programming Languages**, 4. Ed., Addison-Wesley, 1999

U. Kastens: **Übersetzerbau**, Handbuch der Informatik 3.3, Oldenbourg, 1990
(not available on the market anymore, available in the library of the University)

A. W. Appel: **Modern Compiler Implementation in Java**, Cambridge University Press, 2nd Edition, 2002 (available for C and for ML, too)

W. M. Waite, L. R. Carter: **An Introduction to Compiler Construction,** Harper Collins, New York, 1993

U. Kastens, A. M. Sloane, W. M. Waite: **Generating Software from Specifications**, Jones and Bartlett Publishers, 2007

Lecture Programming Languages and Compilers WS 2013/14 / Slide 005

Objectives:

Useful references for the course

In the lecture:

Comments of the course material and books

Questions:

- Find the material in the Web, get used to its structure, place suitable bookmarks.

References forReading

Week	Chapter	Kastens	Waite Carter	Eli Doc.
1	0. Introduction			
2	1. Language Properties and Compiler tasks	1, 2	1.1 - 2.1	
3 - 4	2. Symbol Specification and Lexical Analysis	3	2.4 3.1 - 3.3	+
5 - 7	3. Context-free Grammars and Syntactic Analysis	4	4, 5, 6	+
8 - 10	4. Attribute Grammars and Semantic Analysis	5		+
11	5. Binding of Names	6.2	7	+
12	6. Type Specification and Analysis	(6.1)		+
13	7. Specification of Dynamic Semantics			
13	8. Source-to-Source Translation			
	9. Domain Specific Languages			

Lecture Programming Languages and Compilers WS 2013/14 / Slide 005a

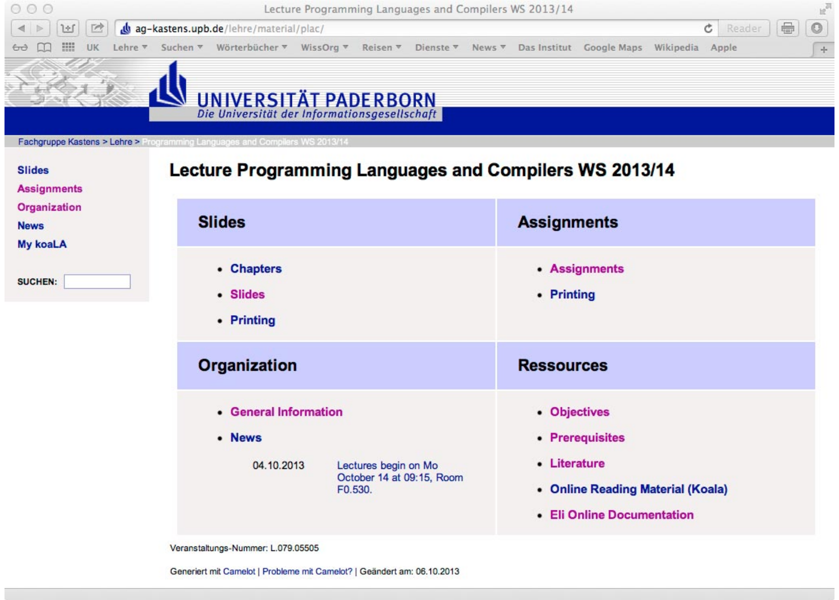
Objectives:

Associate reading material to course topics

In the lecture:

Explain the strategy for using the reading material

Course material in the Web



Lecture Programming Languages and Compilers WS 2013/14 / Slide 006

Objectives:

The root page of the course material.

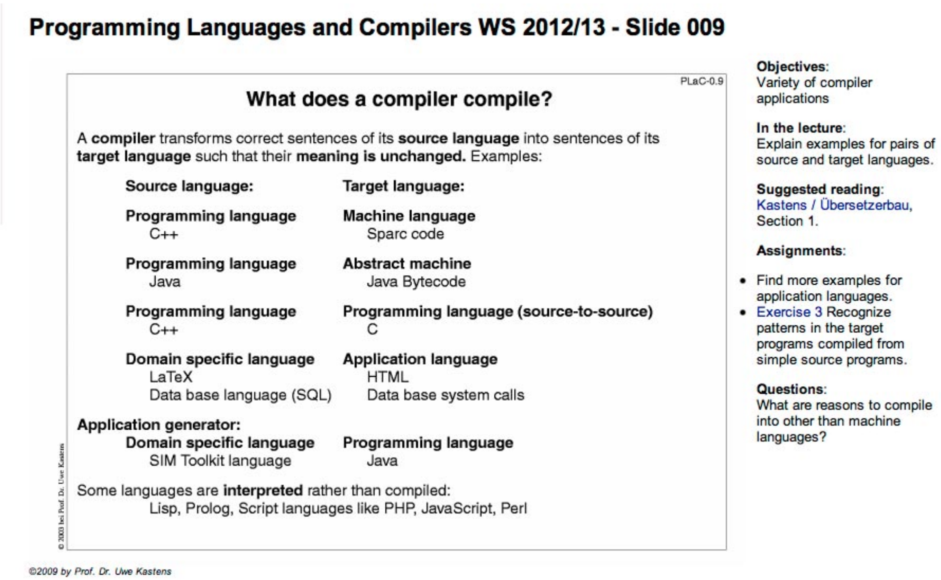
In the lecture:

The navigation structure is explained.

Assignments:

Explore the course material.

Commented slide in the course material



Programming Languages and Compilers WS 2012/13 - Slide 009

PLaC-0.9

What does a compiler compile?

A **compiler** transforms correct sentences of its **source language** into sentences of its **target language** such that their **meaning is unchanged.** Examples:

Source language:	Target language:
Programming language C++	**Machine language** Sparc code
Programming language Java	**Abstract machine** Java Bytecode
Programming language C++	**Programming language (source-to-source)** C
Domain specific language LaTeX, Data base language (SQL)	**Application language** HTML, Data base system calls

Application generator:

Domain specific language SIM Toolkit language	**Programming language** Java

Some languages are **interpreted** rather than compiled: Lisp, Prolog, Script languages like PHP, JavaScript, Perl

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Objectives: Variety of compiler applications

In the lecture: Explain examples for pairs of source and target languages.

Suggested reading: Kastens / Übersetzerbau, Section 1.

Assignments:

- Find more examples for application languages.
- Exercise 3 Recognize patterns in the target programs compiled from simple source programs.

Questions: What are reasons to compile into other than machine languages?

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Lecture Programming Languages and Compilers WS 2013/14 / Slide 007

Objectives:

A slide of the course material.

In the lecture:

The comments are explained.

Assignments:

Explore the course material.

Organization of the course

Programming Languages and Compilers WS 2013/14 - Organization

Lecturer

Prof. Dr. Uwe Kastens:

Office Hours

- `Wed 16.00 - 17.00   F2.308`
- `Tue 11.00 - 12.00   F2.308`

Hours

Lecture

- `V2    Mo 09.15 - 10.45, F0.530`

Start date: Oct 14, 2013

Excercises

- `Ü1   Mo 11.00 - 11.45, F0.530 / F1.520`

Start date: Oct 14, 2013

Examination

Oral examinations of 20 to 30 min duration. Any topic of the lecture and of the tutorial may be subject of the exam. See also the sequence of questions in Chapter 10.

Two time spans are offered for examinations:

1. Feb 12 to 14 in 2014
2. April 01 to 03 in 2014

Register in PAUL for the one or the other time span; then ask for an appointment by email to my secretary Mrs. Gundelach (sigu@upb.de).

Assignments

- Assignments will be published every week.

Lecture Programming Languages and Compilers WS 2013/14 / Slide 008

Objectives:

Know how the course is organized

In the lecture:

Comments on exams and registration

Assignments:

Explore the course material.

What does a compiler compile?

A **compiler** transforms correct sentences of its **source language** into sentences of its **target language** such that their **meaning is unchanged.** Examples:

Source language:	Target language:
Programming language C++	**Machine language** Sparc code
Programming language Java	**Abstract machine** Java Bytecode
Programming language C++	**Programming language (source-to-source)** C
Domain specific language LaTeX Data base language (SQL)	**Application language** HTML Data base system calls

Application generator:

Domain specific language SIM Toolkit language	**Programming language** Java

Some languages are **interpreted** rather than compiled:

Lisp, Prolog, Script languages like PHP, JavaScript, Perl

Lecture Programming Languages and Compilers WS 2013/14 / Slide 009

Objectives:

Variety of compiler applications

In the lecture:

Explain examples for pairs of source and target languages.

Suggested reading:

Kastens / Übersetzerbau, Section 1.

Assignments:

- Find more examples for application languages.
- Exercise 3 Recognize patterns in the target programs compiled from simple source programs.

Questions:

What are reasons to compile into other than machine languages?

What is compiled here?

```
class Average
    { private:
        int sum, count;
      public:
        Average (void)
          { sum = 0; count = 0; }
        void Enter (int val)
         { sum = sum + val; count++; }
        float GetAverage (void)
          { return sum / count; }
    };
--------------
_Enter__7Averagei:
            pushl %ebp
            movl %esp,%ebp
            movl 8(%ebp),%edx
            movl 12(%ebp),%eax
            addl %eax,(%edx)
            incl 4(%edx)
     L6:
            movl %ebp,%esp
            popl %ebp
            ret
```

```
class Average
{ private
    int sum, count;
  public
    Average ()
      { sum = 0; count = 0; }
    void Enter (int val)
      { sum = sum + val; count++; }
    float GetAverage ()
      { return sum / count; }
};
---------------
1: Enter: (int) --> void
   Access: []
   Attribute 'Code' (Length 49)
      Code: 21 Bytes Stackdepth: 3 Locals: 2
      0:    aload_0
      1:    aload_0
      2:    getfield cp4
      5:    iload_1
      6:    iadd
      7:    putfield cp4
      10:   aload_0
      11:   dup
      12:   getfield cp3
      15:   iconst_1
      16:   iadd
```


Lecture Programming Languages and Compilers WS 2013/14 / Slide 010

Objectives:

Recognize examples for compilations

In the lecture:

Anwer the questions below.

Questions:

- Which source and target language are shown here?
- How did you recognize them?

What is compiled here?

```
 program Average;
       var sum, count: integer;
           aver: integer;
       procedure Enter (val: integer);
           begin sum := sum + val;
                 count := count + 1;
           end;
     begin
       sum := 0; count := 0;
       Enter (5); Enter (7);
       aver := sum div count;
     end.
-----------
void ENTER_5 (char *slnk , int VAL_4)
     {
     {/* data definitions: */
        /* executable code: */
        {
           SUM_1 = (SUM_1)+(VAL_4);
           COUNT_2 = (COUNT_2)+(1);
           ;
        }
     }}/* ENTER_5 */
```

```
\documentstyle[12pt]{article}
\begin{document}
\section{Introduction}
This is a very short document.
It just shows
\begin{itemize}
\item an item, and
\item another item.
\end{itemize}
\end{document}

-------------

%%Page: 1 1
1 0 bop 164 315 a Fc(1)81
b(In)n(tro)r(duction)
164 425 y Fb(This)16
b(is)g(a)h(v)o(ery)e(short)
i(do)q(cumen)o(t.)j(It)c(just)g
(sho)o(ws)237 527 y Fa(\017)24 b
Fb(an)17 b(item,)
c(and)237 628 y Fa(\017)24 b
Fb(another)17 b(item.)
961 2607 y(1)p
eop
```


Lecture Programming Languages and Compilers WS 2013/14 / Slide 011

Objectives:

Recognize examples for compilations

In the lecture:

Anwer the questions below.

Questions:

- Which source and target language are shown here?
- How did you recognize them?

Languages for specification and modeling

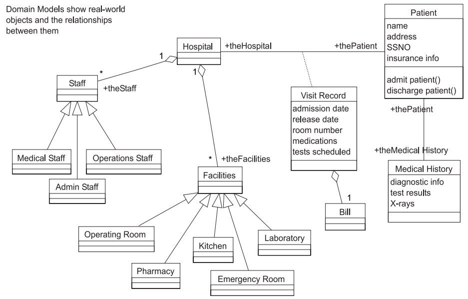
SDL (CCITT)
Specification and Description Language:

```
block Dialogue;
  signal
    Money, Release, Change, Accept, Avail, Unavail, Price,
    Showtxt, Choice, Done, Flushed, Close, Filled;
  process Coins referenced;
  process Control referenced;
  process Viewpoint referenced;
  signalroute Plop
    from env to Coins
      with Coin_10, Coin_50, Coin_100, Coin_x;
  signalroute Pong
    from Coins to env
      with Coin_10, Coin_50, Coin_100, Coin_x;
  signalroute Cash
    from Coins to Control
      with Money, Avail, Unavail, Flushed, Filled;
    from Control to Coins
      with Accept, Release, Change, Close;

  ...

  connect Pay and Plop;
  connect Flush and Pong;
endblock Dialogue;
```

UML
Unified Modeling Language:



Lecture Programming Languages and Compilers WS 2013/14 / Slide 012

Objectives:
Be aware of specification languages

In the lecture:
Comments on SDL and UML

Suggested reading:
Text

Questions:
What kind of tools are needed for such specification languages?

Domain Specific Languages (DSL)

A language designed for a **specific application domain.**
Application Generator: Implementation of a DSL by a **program generator**

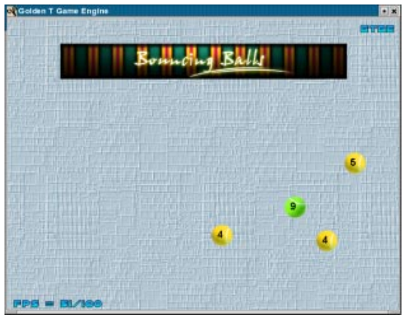
Examples:

- **Simulation of mechatronic feedback systems**
- **Robot control**
- **Collecting data from instruments**
- **Testing car instruments**
- **Game description language**:

```
game BBall
{  size 640 480;
   background "pics/backgroundbb.png";
   Ball einball; int ballsize;

   initial {
      ballsize=36;
   }

  events {
      pressed SPACE:
      { einball = new Ball(<100,540>, <100,380>);
```



Lecture Programming Languages and Compilers WS 2013/14 / Slide 013

Objectives:
Understand DSL by examples

In the lecture:
Explain the examples

Suggested reading:

- C.W. Krueger: Software Reuse, ACM Computing Surveys 24, June 1992
- Conference on DSL (USENIX), Santa Babara, Oct. 1997
- ACM SIGPLAN Workshop on DSL (POPL), Paris, Jan 1997

Questions:
Give examples for tools that can be used for such languages.

Programming languages as source or target languages

Programming languages as source languages:

- **Program analysis**
  call graphs, control-flow graph, data dependencies,
  e. g. for the year 2000 problem
- **Recognition of structures and patterns**
  e. g. for Reengineering

Programming languages as target languages:

- **Specifications (SDL, OMT, UML)**
- **graphic modeling of structures**
- **DSL, Application generator**

=> Compiler task: Source-to-source compilation

Lecture Programming Languages and Compilers WS 2013/14 / Slide 014

Objectives:

Understand programming languages in different roles

In the lecture:

- Comments on the examples
- Role of program analysis in software engineering
- Role of Source-to-source compilation in software engineering

Questions:

Give examples for the use of program analysis in software engineering.

Semester project as running example

SetLan: A Language for Set Computation

SetLan is a domain-specific language for **programming with sets**. Constructs of the the language are dedicated to describe sets and computations using sets. The language allows to define types for sets and variables and expressions of those types. Specific loop constructs allow to iterate through sets. These constructs are embedded in a simple imperative language.

A source-to-source translator **translates SetLan programs into Java** programs.

The SetLan translator is implemented using the methods and tools introduced in this course.

The participants of this course get an implementation of a **sub-language of SetLan as a starting point** for their work towards their individual extension of the language and the implementation.

```
{
   set a, b; int i;
   i = 1;
   a = [i, 3, 5];
   b = [3, 6, 8];
   print a+b; printLn;
   print a*b <= b;
   printLn;
}
```


Lecture Programming Languages and Compilers WS 2013/14 / Slide 015

Objectives:

Get an idea of the task

In the lecture:

- Comment the task description.
- Explain the role of the running example.

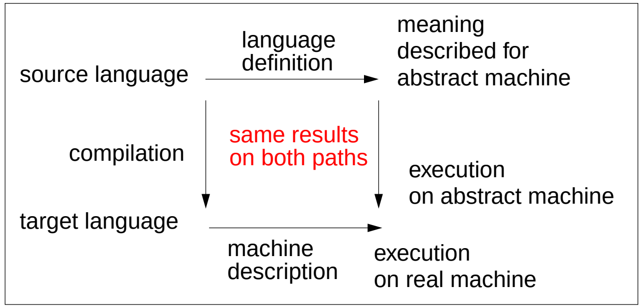
Assignments:

In the tutorial

- Explain the application domain.
- What may a game description contain?
- Give examples for typical language constructs.
- Explore the language.
- Use the language.

1. Language properties - compiler tasks
Meaning preserving transformation

A **compiler** transforms **any correct sentence** of its **source language** into a sentence of its **target language** such that its **meaning is unchanged**.



A **meaning** is defined only for **all correct** programs => compiler task: error handling

Static language properties are analyzed at **compile time,** e. g. definitions of Variables, types of expressions; => determine the transformation, if the program **compilable**

Dynamic properties of the program are determined and checked at **runtime,** e. g. indexing of arrays => determine the effect, if the program **executable** (However, just-in-time compilation for Java: bytecode is compiled at runtime.)

Lecture Programming Languages and Compilers WS 2010/11 / Slide 101

Objectives:

Understand fundamental notions of compilation

In the lecture:

The topics on the slide are explained. Examples are given.

- Explain the role of the arcs in the commuting diagram.
- Distinguish compile time and run-time concepts.
- Discuss examples.

Levels of language properties - compiler tasks

• **a. Notation of tokens** keywords, identifiers, literals formal definition: **regular expressions**	**lexical analysis**
• **b. Syntactic structure** formal definition: **context-free grammar**	**syntactic analysis**
• **c. Static semantics** binding names to program objects, typing rules usually defined by informal texts, formal definition: **attribute grammar**	**semantic analysis, transformation**
• **d. Dynamic semantics** semantics, effect of the execution of constructs usually defined by informal texts in terms of an abstract machine**,** formal definition: **denotational semantics**	**transformation, code generation**
Definition of target language (target machine)	**transformation, code generation** **assembly**

Lecture Programming Languages and Compilers WS 2010/11 / Slide 102

Objectives:

Relate language properties to levels of definitions

In the lecture:

- These are prerequisites of the course "Grundlagen der Programmiersprachen" (see course material GPS-1.16, GPS-1.17).
- Discuss the examples of the following slides under these categories.

Suggested reading:

Kastens / Übersetzerbau, Section 1.2

Assignments:

- Exercise 1 Let the compiler produce error messages for each level.
- Exercise 2 Relate concrete language properties to these levels.

Questions:

Some language properties can be defined on different levels. Discuss the following for hypothetical languages:

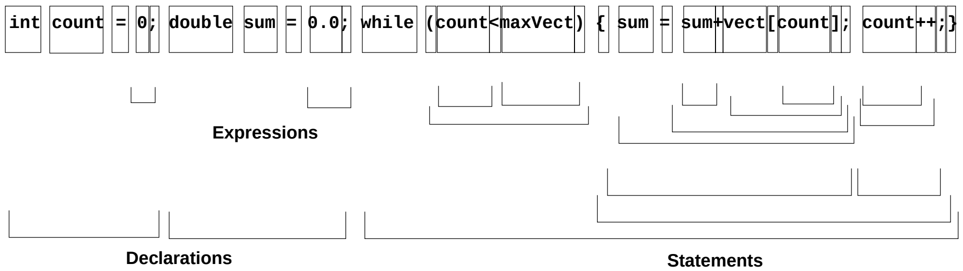
- "Parameters may not be of array type." Syntax or static semantics?
- "The index range of an array may not be empty." Static or dynamic semantics?

Example: Tokens and structure

Character sequence

```
int count = 0; double sum = 0.0; while (count<maxVect) { sum = sum+vect[count]; count++;}
```

Tokens



Structure

Lecture Programming Languages and Compilers WS 2010/11 / Slide 103

Objectives:

Get an idea of the structuring task

In the lecture:

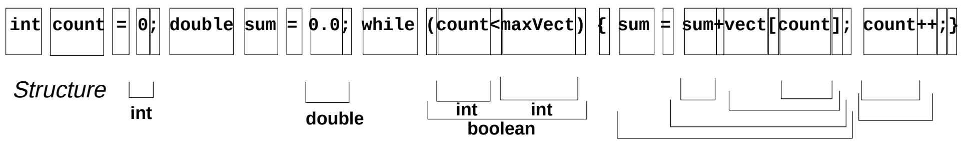
Some requirements for recognizing tokens and deriving the program structure are discussed along the example:

- kinds of tokens,
- characters between tokens,
- nested structure

Questions:

Where do you find the exact requirements for the structuring tasks?

Example: Names, types, generated code



k1: (count, local variable, int)
k2: (sum, local variable, double)

k3: (maxVect, member variable, int)
k4: (vect, member variable, double array)

...

Static properties: names and types

generated Bytecode

```
0 iconst_0
1 istore_1
2 dconst_0
3 dstore_2
4 goto 19
7 dload_2
8 getstatic #5 <vect[]>
11 iload_1
12 faload
13 f2d
14 dadd
15 dstore_2
16 iinc 1 1
19 iload_1
20 getstatic #4 <maxVect>
23 if_icmplt 7
```


Lecture Programming Languages and Compilers WS 2010/11 / Slide 104

Objectives:

Get an idea of the name analysis and transformation task

In the lecture:

Some requirements for these tasks are discussed along the example:

- program objects and their properties,
- program constructs and their types
- target program

Questions:

- Why is the name (e.g. count) a property of a program object (e.g. k1)?
- Can you impose some structure on the target code?

Compiler tasks

Structuring	Lexical analysis	Scanning Conversion
	Syntactic analysis	Parsing Tree construction
Translation	Semantic analysis	Name analysis Type analysis
	Transformation	Data mapping Action mapping
Encoding	Code generation	Execution-order Register allocation Instruction selection
	Assembly	Instruction encoding Internal Addressing External Addressing

Lecture Programming Languages and Compilers WS 2010/11 / Slide 105

Objectives:

Language properties lead to decomposed compiler tasks

In the lecture:

- Explain tasks of the rightmost column.
- Relate the tasks to chapters of the course.

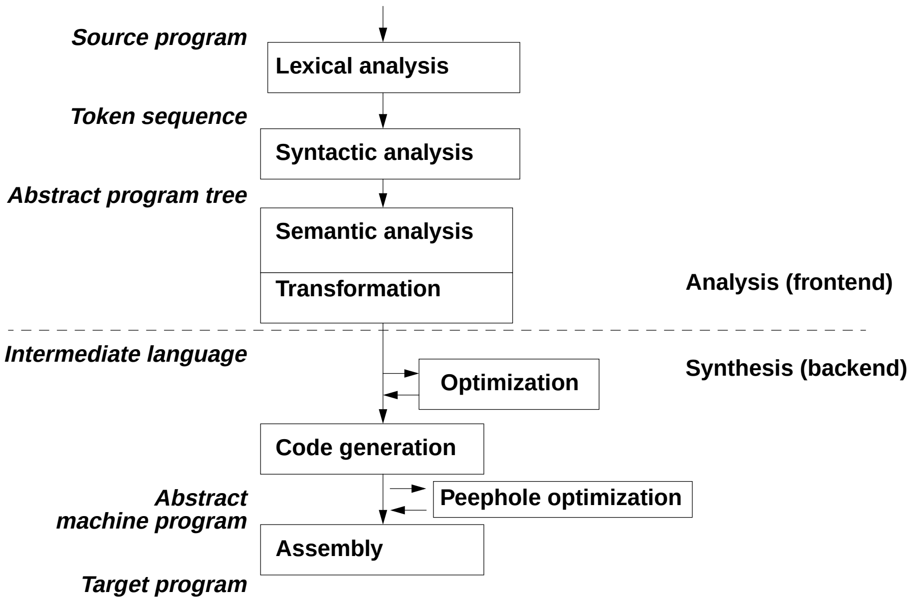
Suggested reading:

Kastens / Übersetzerbau, Section 2.1

Assignments:

Learn the German translations of the technical terms.

Compiler structure and interfaces



Lecture Programming Languages and Compilers WS 2010/11 / Slide 106

Objectives:

Derive compiler modules from tasks

In the lecture:

In this course we focus on the analysis phase (frontend).

Suggested reading:

Kastens / Übersetzerbau, Section 2.1

Assignments:

Compare this slide with U-08 and learn the translations of the technical terms used here.

Questions:

Use this information to explain the example on slides PLaC-1.3, 1.4

Software qualities of the compiler

- **Correctness** Compiler translates correct programs correctly; rejects wrong programs and gives error messages
- **Efficiency** Storage and time used by the compiler
- **Code efficiency** Storage and time used by the generated code; compiler task: optimization
- **User support** Compiler task: Error handling (recognition, message, recovery)
- **Robustness** Compiler gives a reasonable reaction on every input; does not break on any program

Lecture Programming Languages and Compilers WS 2010/11 / Slide 107

Objectives:

Consider compiler as a software product

In the lecture:

Give examples for the qualities.

Questions:

Explain: For a compiler the requirements are specified much more precisely than for other software products.

Strategies for compiler construction

- **Obey exactly to the language definition**
- **Use generating tools**
- **Use standard components**
- **Apply standard methods**
- **Validate the compiler against a test suite**
- **Verify components of the compiler**

Lecture Programming Languages and Compilers WS 2010/11 / Slide 108

Objectives:

Apply software methods for compiler construction

In the lecture:

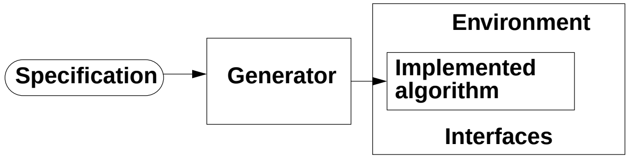
It is explained that effective construction methods exist especially for compilers.

Questions:

What do the specifications of the compiler tasks contribute to more systematic compiler construction?

Generate from specifications

Pattern:



Typical compiler tasks solved by generators:

Regular expressions	**Scanner generator**	Finite automaton
Context-free grammar	**Parser generator**	Stack automaton
Attribute grammar	**Attribute evaluator generator**	Tree walking algorithm
Code patterns	**Code selection generator**	Pattern matching

integrated system Eli:

Lecture Programming Languages and Compilers WS 2010/11 / Slide 109

Objectives:

Usage of generators in compiler construction

In the lecture:

The topics on the slide are explained. Examples are given.

Suggested reading:

Kastens / Übersetzerbau, Section 2.5

Assignments:

- Exercise 5: Find as many generators as possible in the Eli system.

Compiler Frameworks (Selection)

Amsterdam Compiler Kit: (Uni Amsterdam)
The Amsterdam Compiler Kit is fast, lightweight and retargetable compiler suite and toolchain written by Andrew Tanenbaum and Ceriel Jacobs.
Intermediate language EM, set of frontends and backends

ANTLR: (Terence Parr, Uni San Francisco)
ANother Tool for Language Recognition, (formerly PCCTS) is a language tool that provides a framework for constructing recognizers, compilers, and translators from grammatical descriptions containing Java, C#, C++, or Python actions

CoCo: (Uni Linz)
Coco/R is a compiler generator, which takes an attributed grammar of a source language and generates a scanner and a parser for this language. The scanner works as a deterministic finite automaton. The parser uses recursive descent.

Eli: (Unis Boulder, Paderborn, Sydney)
Combines a variety of standard tools that implement powerful compiler construction strategies into a domain-specific programming environment called Eli. Using this environment, one can automatically generate complete language implementations from application-oriented specifications.

SUIF: (Uni Stanford)
The SUIF 2 compiler infrastructure project is co-funded by DARPA and NSF.
It is a free infrastructure designed to support collaborative research in optimizing and parallelizing compilers.

Lecture Programming Languages and Compilers WS 2010/11 / Slide 109a

Objectives:

General information on compiler tool kits

In the lecture:

Some characteristics of the systems are explained.

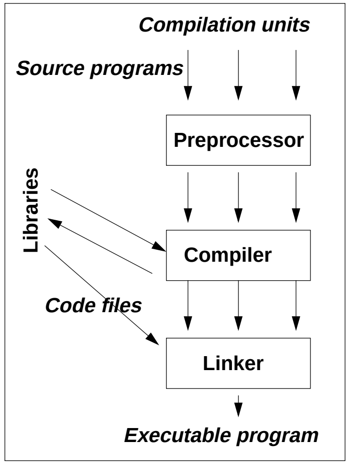
Suggested reading:

Kastens / Übersetzerbau, Section 2.5

Assignments:

- Find more information on the system in the Web

Environment of compilers



Preprocessor cpp substitutes text macros in source programs, e.g.

```
#include <stdio.h>
#include "module.h"

#define SIZE 32
#define SEL(ptr,fld) ((ptr)->fld)
```

Separate compilation of compilation units

- with interface specification, consistency checks, and language specific linker: Modula, Ada, Java
- without ...; checks deferred to system linker: C, C++

Lecture Programming Languages and Compilers WS 2010/11 / Slide 110

Objectives:

Understand the cooperation between compilers and other language tools

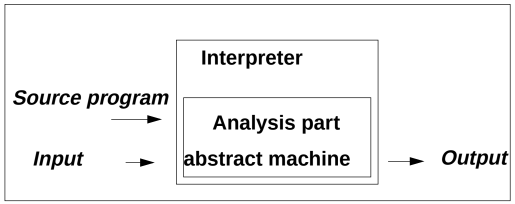
In the lecture:

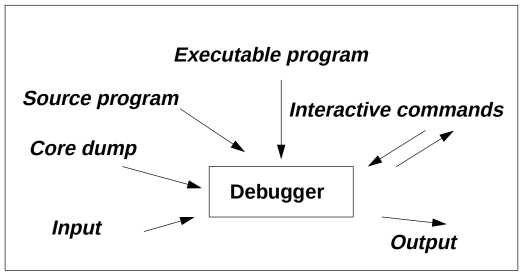
- Explain the roles of language tools
- Explain the flow of information

Suggested reading:

Kastens / Übersetzerbau, Section 2.4

Interpreter and Debugger





Lecture Programming Languages and Compilers WS 2010/11 / Slide 110a

Objectives:

Understand the cooperation between compilers and other language tools

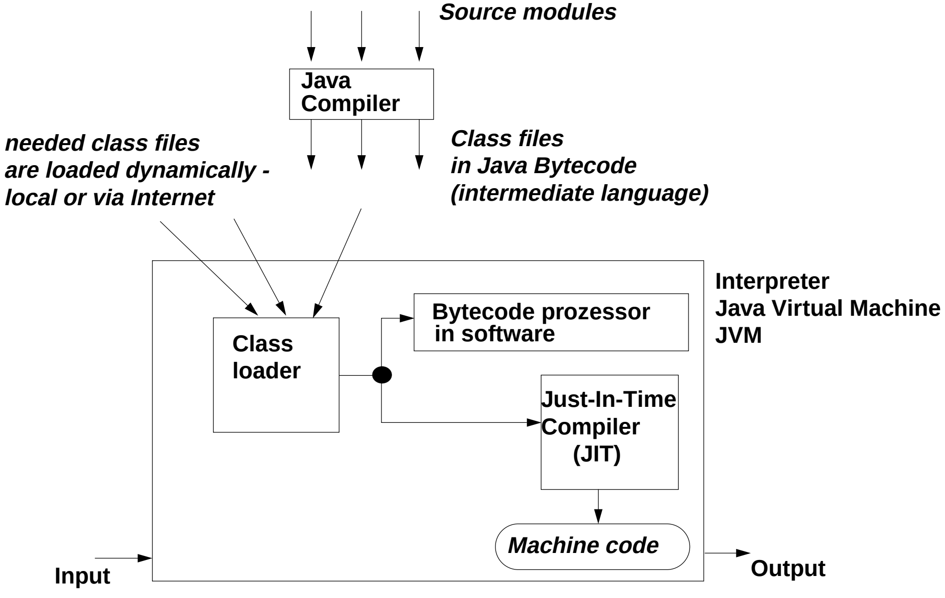
In the lecture:

- Explain the roles of language tools
- Explain the flow of information

Suggested reading:

Kastens / Übersetzerbau, Section 2.4

Compilation and interpretation of Java programs



Lecture Programming Languages and Compilers WS 2010/11 / Slide 111

Objectives:

Special situation for Java

In the lecture:

Explain the role of the absctract machine JVM:

- Interpretation of bytecode.
- JIT: Compiles and optimizes while executing the program.
- JVM: Loads class files while executing the program.

Questions:

- explain why the JVM can not rely on the type checks made by a compiler.

2. Symbol specifications and lexical analysis

Notations of tokens is specified by regular expressions

Token classes: keywords (**`for`**, **`class`**), operators and delimiters (**`+`**, **`==`**, **`;`**, **`{`**), identifiers (**`getSize`**, **`maxint`**), literals (**`42`**, **`'\n'`**)

Lexical analysis isolates tokens within a stream of characters and encodes them:

Tokens

```
int count = 0; double sum = 0.0; while (count<maxVect) { sum = sum+vect[count]; count++;}
```


Lecture Programming Languages and Compilers WS 2011/12 / Slide 201

Objectives:

Introduction of the task of lexical analysis

In the lecture:

Explain the example

Lexical Analysis

Input: ***Program represented by a sequence of characters***

Tasks:	**Compiler modul:**
	Input reader
Recognize and classify tokens Skip irrelevant characters	Scanner (central phase, finite state machine)
Encode tokens:	
	Identifier modul
Store token information	Literal modules
Conversion	String storage

Output: ***Program represented by a sequence of encoded tokens***

Lecture Programming Languages and Compilers WS 2011/12 / Slide 202

Objectives:

Understand lexical analysis subtasks

In the lecture:

Explain

- subtasks and their interfaces using example of PLaC-201,
- different forms of comments,
- sparation of tokens in FORTRAN,

Suggested reading:

Kastens / Übersetzerbau, Section 3, 3.3.1

Avoid context dependent token specifications

Tokens should be **recognized in isolation**:

e. G. all occurrences of the identifier **a** get the same encoding:

```
{int a; ... a = 5; ... {float a; ... a = 3.1; ...}}
```

distinction of the two different variables would require information from semantic analysis

typedef problem in C:

The C syntax requires **lexical distinction** of type-names and other names:

```
typedef int *T; T (*B); X (*Y);
```

cause syntactically different structures: declaration of variable **B** and call of function **X**.
Requires feedback from semantic analysis to lexical analysis.

Identifiers in PL/1 may **coincide with keywords**:

```
if if = then then then := else else else := then
```

Lexical analysis needs feedback from syntactic analysis to distinguish them.

Token separation in FORTRAN:

„Deletion or insertion of blanks does not change the meaning.“

`DO 24 K = 1,5`	begin of a loop, 7 tokens
`DO 24 K = 1.5`	assignment to the variable **DO24K**, 3 tokens

Token separation is determined late.

Lecture Programming Languages and Compilers WS 2011/12 / Slide 203

Objectives:

Recognize difficult specifications

In the lecture:

Explain

- isolated recognition and encoding of tokens,
- feedback of information,
- unusual notation of keywords,
- separation of tokens in FORTRAN,

Suggested reading:

Kastens / Übersetzerbau, Section 3, 3.3.1

Questions:

- Give examples of context dependent information about tokens, which the lexical analysis can not know.
- Some decisions on the notation of tokens and the syntax of a language may complicate lexical analysis. Give examples.
- Explain the typedef problem in C.

Representation of tokens

Uniform encoding of tokens by triples:

Syntax code	**attribute**	**source position**
terminal code of the concrete syntax	value or reference into data module	to locate error messages of later compiler phases

Examples:

```
double sum = 5.6e-5;
while (count < maxVect)
{ sum = sum + vect[count];
```

DoubleToken		12, 1
Ident	138	12, 8
Assign		12, 12
FloatNumber	16	12, 14
Semicolon		12, 20
WhileToken		13, 1
OpenParen		13, 7
Ident	139	13, 8
LessOpr		13, 14
Ident	137	13, 16
CloseParen		13, 23
OpenBracket		14, 1
Ident	138	14, 3

Lecture Programming Languages and Compilers WS 2011/12 / Slide 204

Objectives:

Understand token representation

In the lecture:

Explain the roles of the 3 components using the examples

Suggested reading:

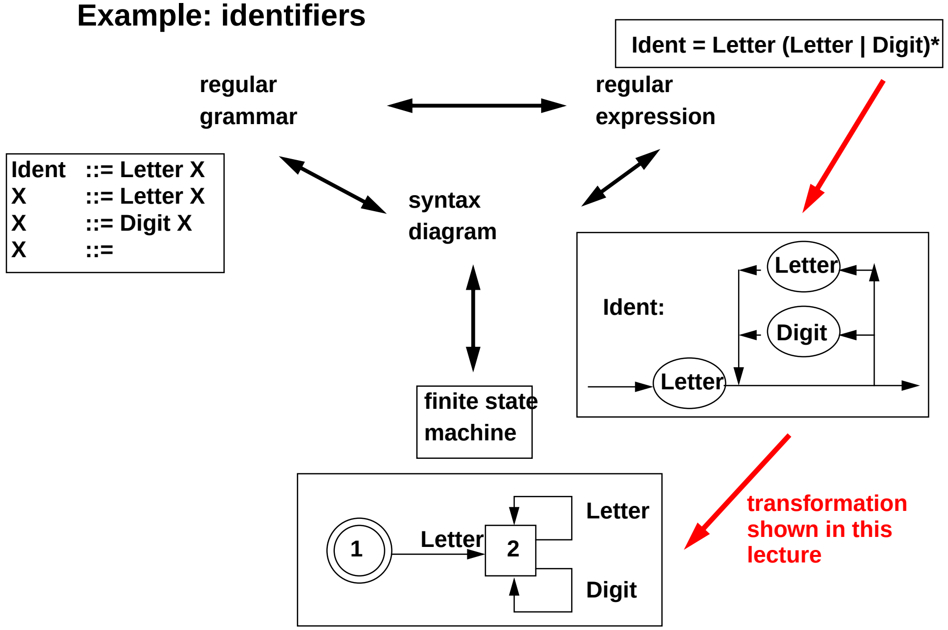
Kastens / Übersetzerbau, Section 3, 3.3.1

Questions:

- What are the requirements for the encoding of identifiers?
- How does the identifier module meet them?
- Can the values of integer literals be represented as attribute values, or do we have to store them in a data module? Explain! Consider also cross compilers!

Specification of token notations

Example: identifiers



Lecture Programming Languages and Compilers WS 2011/12 / Slide 205

Objectives:

Equivalent forms of specification

In the lecture:

- Repeat calculi of the lectures "Modellierung" and "Berechenbarkeit und formale Sprachen".
- Our strategy: Specify regular expressions, transform into syntax diagrams, and from there into finite state machines

Suggested reading:

Kastens / Übersetzerbau, Section 3.1

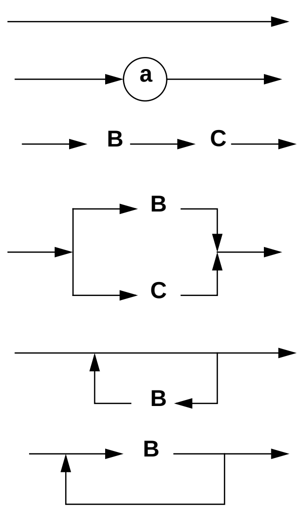
Questions:

- Give examples for Unix tools which use regular expressions to describe their input.

Regular expressions mapped to syntax diagrams

Transformation rules:

regular expression A — **syntax diagram for A**



regular expression A		
empty		**empty**
a		**single character**
B C		**sequence**
B | C		**alternative**
B*		**repetition, may be empty**
B$^+$		**repetition, non-empty**

Lecture Programming Languages and Compilers WS 2011/12 / Slide 206

Objectives:

Construct by recursive substitution

In the lecture:

- Explain the construction for floating point numbers of Pascal.

Suggested reading:

Kastens / Übersetzerbau, Section 3.1

Assignments:

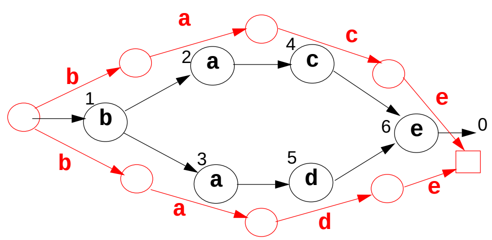
- Apply the technique Exercise 6

Questions:

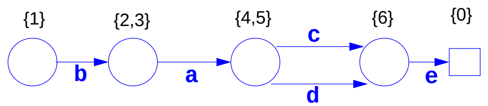
- If one transforms syntax diagrams into regular expressions, certain structures of the diagram require duplication of subexpressions. Give examples.
- Explain the analogy to control flows of programs with labels, jumps and loops.

Naive transformation

1. Transform a **syntax diagram into a non-det. FSM** by naively exchanging nodes and arcs



2. Transform a non-det. FSM into a det. FSM:
Merge equivalents sets of nodes into nodes.



Syntax diagram	**deterministic finite state machine**
set of nodes m_q	state q
sets of nodes m_q and m_r connected with the same character a	transition q ---> r with character a

Lecture Programming Languages and Compilers WS 2011/12 / Slide 207

Objectives:

Understand the transformation method

In the lecture:

- Explain the naive idea with a small artificial example

Suggested reading:

Kastens / Übersetzerbau, Section 3.2

Assignments:

- Apply the method Exercise 6

Questions:

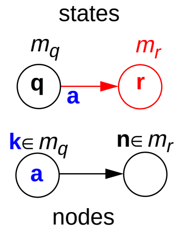
- Why does the naive method may yield non-deterministic automata?

Construction of deterministic finite state machines

Syntax diagram	deterministic finite state machine
set of nodes m_q	state q
sets of nodes m_q and m_r connected with the same character *a*	transitions q ---> r with character *a*

Construction:

1. **enumerate nodes**; exit of the diagram gets the number *0*
2. **initial set of nodes** m_1 contains all nodes that are reachable from the begin of the diagram; m_1 represents the **initial state 1**.
3. **construct new sets of nodes (states)** and **transitions:**
   - chose state *q* with m_q, chose a character *a*
   - consider the set of nodes with character *a*, s.t. their labels *k* are in m_q.
   - consider all nodes that are directly reachable from those nodes; let m_r be the set of their labels
   - create a state *r* for m_r and a transition from *q* to *r* under *a*.
4. **repeat step 3** until no new states or transitions can be created
5. a state *q* is a **final state** iff *0* is in m_q.



Lecture Programming Languages and Compilers WS 2011/12 / Slide 207a

Objectives:

Understand the transformation method

In the lecture:

- Explain the method using floating point numbers of Pascal (PLaC-2.8)
- Recall the method presented in the course "Modellierung".

Suggested reading:

Kastens / Übersetzerbau, Section 3.2

Assignments:

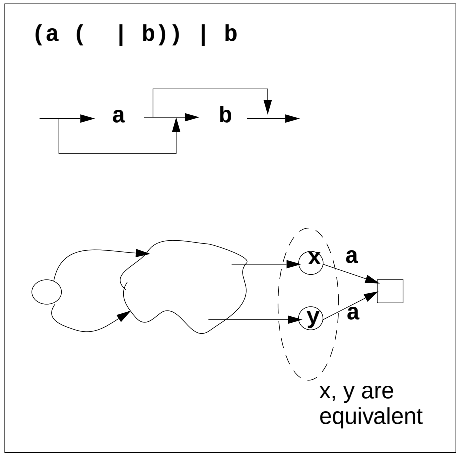
- Apply the method Exercise 6

Questions:

- Why does the method yield deterministic automata?

Properties of the transformation

1. **Syntax diagrams** can express languages **more compact** than regular expressions can:
   A regular expression for { a, ab, b} needs more than one occurrence of a or b -
   a syntax diagram doesn't.
2. The FSM resulting from a transformation of PLaC 2.7a may have m**ore states than necessary**.
3. There are transformations that **minimize the number of states** of any FSM.



Lecture Programming Languages and Compilers WS 2011/12 / Slide 207b

Objectives:

Understand the transformation method

In the lecture:

- Explain the properties.
- Recall the algorithm.

Suggested reading:

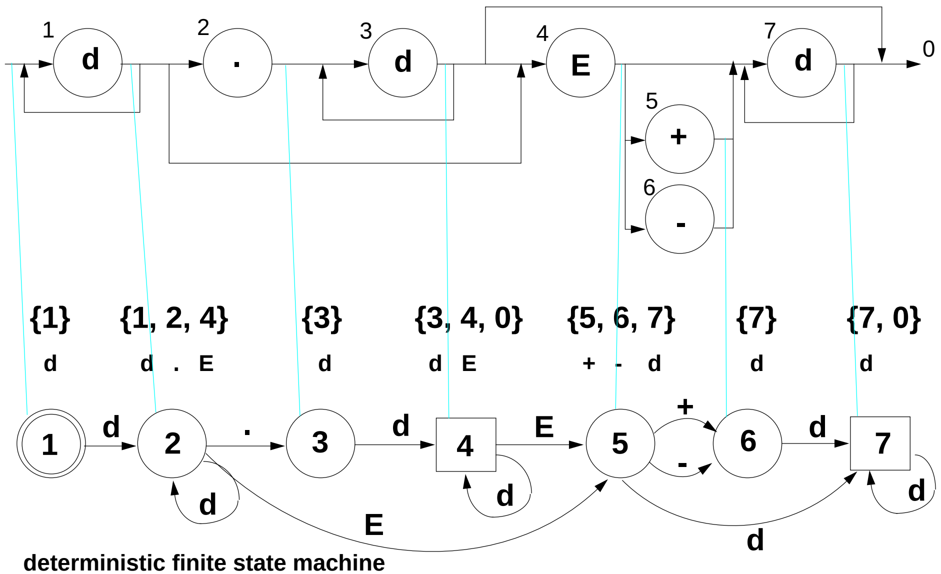
Kastens / Übersetzerbau, Section 3.2

Assignments:

- Apply the method Exercise 6

Example: Floating point numbers in Pascal

Syntax diagram



deterministic finite state machine

Lecture Programming Languages and Compilers WS 2011/12 / Slide 208

Objectives:

Understand the construction method

In the lecture:

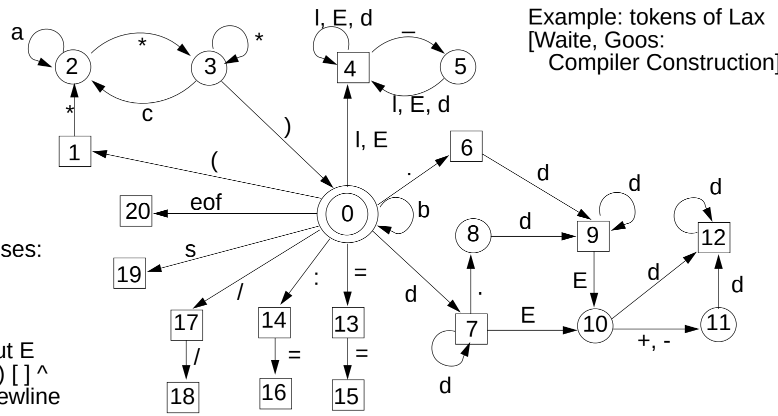
The construction process of the previous slide is explained using this example.

Composition of token automata

Construct one finite state machine for each token. Compose them forming a single FSM:

- **Identify the initial states of the single automata** and identical structures evolving from there (transitions with the same character and states).
- **Keep the final states of single automata distinct,** they classify the tokens.
- **Add automata for comments and irrelevant characters** (white space)

Example: tokens of Lax
[Waite, Goos:
Compiler Construction]



character classes:

a all but *
c all but * or)
d digits
l all letters but E
s + - * < > ; ,) [ ] ^
b blank tab newline

Lecture Programming Languages and Compilers WS 2011/12 / Slide 209

Objectives:

Construct a multi-token automaton

In the lecture:

Use the example to

- discuss the composition steps,
- introduce the abbreviation by character classes,
- to see a non-trivial complete automaton.

Suggested reading:

Kastens / Übersetzerbau, Section 3.2

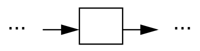
Questions:

Describe the notation of Lax tokens and comments in English.

Rule of the longest match

An automaton may contain **transitions from final states:**

When does the automaton stop?



Rule of the longest match:

- **The automaton continues as long as there is a transition with the next character.**
- **After having stopped it sets back to the most recently passed final state.**
- **If no final state has been passed an error message is issued.**

Consequence: Some kinds of tokens have to be separated explicitly.

Check the concrete grammar for tokens that may occur adjacent!

Lecture Programming Languages and Compilers WS 2011/12 / Slide 210

Objectives:

Understand the consequences of the rule

In the lecture:

- Discuss examples for the rule of the longest match.
- Discuss different cases of token separation.

Suggested reading:

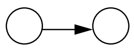
Kastens / Übersetzerbau, Section 3.2

Questions:

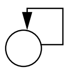
- Point out applications of the rule in the Lax automaton, which arose from the composition of sub-automata.
- Which tokens have to be separated by white space?

Scanner: Aspects of implementation

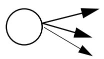
- **Runtime is proportional to the number of characters in the program**
- **Operations per character must be fast** - otherwise the Scanner dominates compilation time
- **Table driven** automata are too **slow:**
  Loop interprets table, 2-dimensional array access, branches
- **Directly programmed** automata is **faster;** transform **transitions into control flow:**



sequence



repeat loop



branch, switch

- **Fast loops** for sequences of irrelevant **blanks**.
- Implementation of **character classes**:
  bit pattern or indexing - avoid slow operations with sets of characters.
- **Do not copy characters** from input buffer - maintain a pointer into the buffer, instead.

Lecture Programming Languages and Compilers WS 2011/12 / Slide 211

Objectives:

Runtime efficiency is important

In the lecture:

- Advantages of directly programmed automata. Compare to table driven.

Suggested reading:

Kastens / Übersetzerbau, Section 3.3

Assignments:

- Generate directly programmed automata Exercise 7

Questions:

- Are there advantages for table-driven automata? Check your arguments carefully!

Characteristics of Input Data

Table 7
Characteristics of the Input Data

	P4		SYNPUT	
	Occurrences	Characters	Occurrences	Characters
Single spaces	11404	11404	2766	2766
Identifiers	8411	41560	5799	22744
Keywords	4183	15080	2034	7674
>3 spaces	3850	60694	1837	19880
;	2708	2708	1880	1880
:=	1379	2758	966	1932
Integers	1354	2202	527	573
(	1245	1245	751	751
)	1245	1245	751	751
,	1032	1032	842	842
comments	659	13765	675	35066
[	654	654	218	218
]	654	654	218	218
:	635	635	483	483
.	546	546	400	400
Strings	493	2560	303	3017
Space pairs	470	940	39	78
=	438	438	206	206
^	353	353	461	461
<>	213	426	96	192
+	203	203	183	183
-	82	82	61	61
Space triples	56	168	842	2526
..	37	74	21	42
<=	26	52	5	10
>	18	18	27	27
<	14	14	25	25
*	10	10	12	12
>=	5	10	7	14
Reals	0	0	3	14
/	0	0	1	1

significant numbers of characters

W. M. Waite:
The Cost of Lexical Analysis.
Software- Practice and Experience,
16(5):473-488, May 1986.

Lecture Programming Languages and Compilers WS 2011/12 / Slide 211b

Objectives:

Profile how characters contribute to tokens

In the lecture:

- Measurements on occurrences of symbols: Single spaces, identifiers, keywords, squences of spaces are most frequent. Comments contribute most characters.

Suggested reading:

Kastens / Übersetzerbau, Section 3.3

Identifier module and literal modules

- **Uniform interface for all scanner support modules:**
  Input parameters: pointer to token text and its length;
  Output parameters: syntax code, attribute
- **Identifier module encodes identifier occurrences bijective (1:1), and recognizes keywords**
  Implementation: hash vector, extensible table, collision lists
- **Literal modules for floating point numbers, integral numbers, strings**

  Variants for representation in memory:
  token text; value converted into compiler data; value converted into target data

  Caution:
  Avoid overflow on conversion!
  Cross compiler: compiler representation may differ from target representation
- **Character string memory:**
  stores strings without limits on their lengths,
  used by the identifier module and the literal modules

Lecture Programming Languages and Compilers WS 2011/12 / Slide 212

Objectives:

Safe and efficient standard implementations are available

In the lecture:

- Give reasons for the implementation techniques.
- Show different representations of floating point numbers.
- Escape characters in strings need conversion.

Suggested reading:

Kastens / Übersetzerbau, Section 3.3

Questions:

- Give examples why the analysis phase needs to know values of integral literals.
- Give examples for representation of literals and their conversion.

Scanner generators

generate the central function of lexical analysis

- **GLA** University of Colorado, Boulder; component of the Eli system
- **Lex** Unix standard tool
- **Flex** Successor of Lex
- **Rex** GMD Karlsruhe

Token specification: regular expressions

- **GLA** library of precoined specifications; recognizers for some tokens may be programmed
- **Lex, Flex, Rex** transitions may be made conditional

Interface:

- **GLA** as described in this chapter; cooperates with other Eli components
- **Lex, Flex, Rex** actions may be associated with tokens (statement sequences) interface to parser generator Yacc

Implementation:

- **GLA** directly programmed automaton in C
- **Lex, Flex, Rex** table-driven automaton in C
- **Rex** table-driven automaton in C or in Modula-2
- **Flex, Rex** faster, smaller implementations than generated by Lex

Lecture Programming Languages and Compilers WS 2011/12 / Slide 213

Objectives:

Know about the most common generators

In the lecture:

Explain specific properties mentioned here.

Suggested reading:

Kastens / Übersetzerbau, Section 3.4

Assignments:

Use GLA and Lex Exercise 7

3. Context-free Grammars and Syntactic Analysis

Input: **token sequence**

Tasks:

Parsing: construct a derivation according to the **concrete syntax**,
Tree construction: build a structure tree according to the **abstract syntax**,
Error handling: detection of an error, message, recovery

Result: **abstract program tree**

Compiler module parser:

deterministic stack automaton, augmented by actions for tree construction

top-down parsers: leftmost derivation; tree construction top-down or bottom-up

bottom-up parsers: rightmost derivation backwards; tree construction bottom-up

Abstract program tree (condensed derivation tree):
represented by a

- **data structure in memory** for the translation phase to operate on,
- linear **sequence of nodes on a file** (costly in runtime),
- **sequence of calls** of functions of the translation phase.

Lecture Programming Languages and Compilers WS 2013/14 / Slide 301

Objectives:

Relation between parsing and tree construction

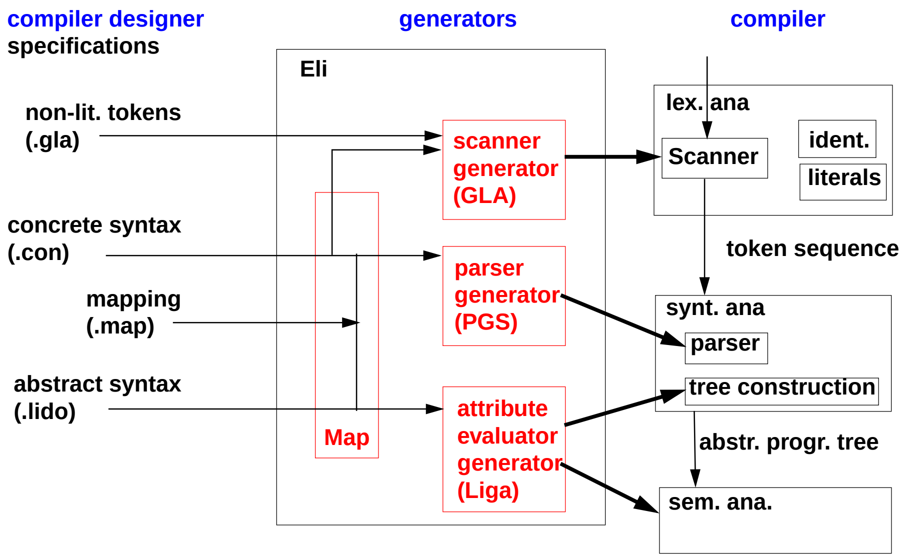
In the lecture:

- Explain the tasks, use example on PLaC-1.3.
- Sources of prerequisites:
- context-free grammars: "Grundlagen der Programmiersprachen (2nd Semester), or "Berechenbarkeit und formale Sprachen" (3rd Semester),
- Tree representation in prefix form, postfix form: "Modellierung" (1st Semester).

Suggested reading:

Kastens / Übersetzerbau, Section 4.1

Generating the structuring phase from specifications (Eli)



Lecture Programming Languages and Compilers WS 2013/14 / Slide 301a

Objectives:

Understand how generators build the structuring phase

In the lecture:

Explain

- the flow of information from the specifications to the generators,
- the generated products in the compiler.

Suggested reading:

Kastens / Übersetzerbau, Section 4.1

3.1 Concrete and abstract syntax

concrete syntax	abstract syntax
- context-free grammar	- context-free grammar
- defines the structure of source programs	- defines abstract program trees
- is unambiguous	- is usually ambiguous
- specifies derivation and parser	- translation phase is based on it
- parser actions specify the tree construction --->	- tree construction
- some chain productions have only syntactic purpose `Expr ::= Fact` have no action	no node created
- symbols are mapped `{Expr,Fact}` ->	to one abstract symbol `Exp`

- same action at structural equivalent productions:
`Expr ::= Expr AddOpr Fact &BinEx`
`Fact ::= Fact MulOpr Opd  &BinEx`
	- creates tree nodes

- semantically relevant chain productions, e.g. `ParameterDecl ::= Declaration`	- are kept (tree node is created)
- terminal symbols identifiers, literals, keywords, special symbols	- only semantically relevant ones are kept identifiers, literals
- concrete syntax and symbol mapping specify	- abstract syntax (can be generated)

Lecture Programming Languages and Compilers WS 2013/14 / Slide 302

Objectives:

Distinguish roles and properties of concrete and abstract syntax

In the lecture:

- Use the expression grammar of PLaC-3.3, PLaC-3.4 for comparison.
- Construct abstract syntax systematically.
- Context-free grammars specify trees - not only strings! Is also used in software engineering to specify interfaces.

Suggested reading:

Kastens / Übersetzerbau, Section 4.1

Assignments:

- Generate abstract syntaxes from concrete syntaxes and symbol classes.
- Use Eli for that task. Exercise 10

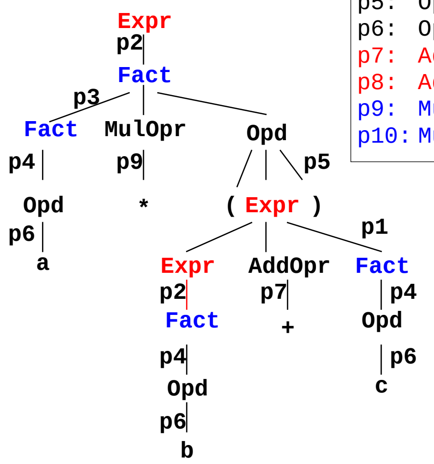
Questions:

- Why is no information lost, when an expression is represented by an abstract program tree?
- Give examples for semantically irrelevant chain productions outside of expressions.
- Explain: XML-based languages are defined by context-free grammars. Their sentences are textual representations of trees.

Example: concrete expression grammar

name	production	action
p1:	`Expr ::= Expr AddOpr Fact`	*BinEx*
p2:	`Expr ::= Fact`	
p3:	`Fact ::= Fact MulOpr Opd`	*BinEx*
p4:	`Fact ::= Opd`	
p5:	`Opd ::= '(' Expr ')'`	
p6:	`Opd ::= Ident`	*IdEx*
p7:	`AddOpr ::= '+'`	*PlusOpr*
p8:	`AddOpr ::= '-'`	*MinusOpr*
p9:	`MulOpr ::= '*'`	*TimesOpr*
p10:	`MulOpr ::= '/'`	*DivOpr*

derivation tree for `a * (b + c)`



`+, - lower precedence`
`*, / higher precedence`

Lecture Programming Languages and Compilers WS 2013/14 / Slide 303

Objectives:

Illustrate comparison of concrete and abstract syntax

In the lecture:

- Repeat concepts of "GdP" (slide GdP-2.5): Grammar expresses operator precedences and associativity.
- The derivation tree is constructed by the parser - not necessarily stored as a data structure.
- Chain productions have only one non-terminal symbol on their right-hand side.

Suggested reading:

Kastens / Übersetzerbau, Section 4.1

Suggested reading:

slide GdP-2.5

Questions:

- How does a grammar express operator precedences and associativity?
- What is the purpose of the chain productions in this example.
- What other purposes can chain productions serve?

Patterns for expression grammars

Expression grammars are **systematically** constructed,
such that **structural properties** of expressions are defined:

one level of precedence, **binary** operator, left-associative:

```
A ::= A Opr B
A ::= B
```

one level of precedence, **binary** operator, right-associative:

```
A ::= B Opr A
A ::= B
```

one level of precedence, **unary Operator**, prefix:

```
A ::= Opr A
A ::= B
```

one level of precedence, **unary Operator**, postfix:

```
A ::= A Opr
A ::= B
```

Elementary operands: **only derived** from the nonterminal of the **highest precedence** level (be H here):

```
H ::= Ident
```

Expressions in parentheses: only derived from the nonterminal of the **highest precedence** level (assumed to be H here); **contain** the nonterminal of the **lowest precedence level** (be A here):

```
H ::= '(' A ')'
```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Objectives:

Be able to apply the patterns

In the lecture:

Explain the patterns

Assignments:

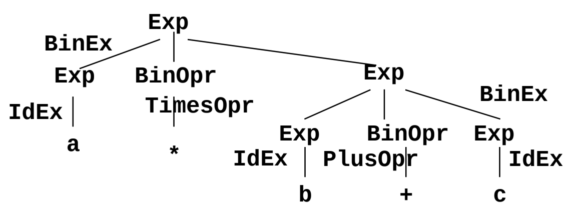
Apply the patterns to understand given and construct new expression grammars.

Example: abstract expression grammar

name **production**

```
BinEx:     Exp    ::= Exp BinOpr Exp
IdEx:      Exp    ::= Ident
PlusOpr:   BinOpr ::= '+'
MinusOpr:  BinOpr ::= '-'
TimesOpr:  BinOpr ::= '*'
DivOpr:    BinOpr ::= '/'
```

abstract program tree for `a * (b + c)`



symbol classes:
```
Exp = { Expr, Fact, Opd }
BinOpr = { AddOpr, MulOpr }
```

Actions of the concrete syntax: **productions** of the abstract syntax to create tree nodes for
no action at a concrete chain production: **no tree node** is created

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Objectives:

Illustrate comparison of concrete and abstract syntax

In the lecture:

- Repeat concepts of "GdP" (slide GdP-2.9):
- Compare grammars and trees.
- Actions create nodes of the abstract program tree.
- Symbol classes shrink node pairs that represent chain productions into one node

Suggested reading:

Kastens / Übersetzerbau, Section 4.1

Suggested reading:

slide GdP-2.9

Questions:

- Is this abstract grammar unambiguous?
- Why is that irrelevant?

3.2 Design of concrete grammars

Objectives

The concrete grammar for **parsing**

- is parsable: fulfills the **grammar condition** of the chosen parser generator;
- specifies the **intended language** - or a small super set of it;
- is provably related to the **documented grammar**;
- can be **mapped to** a suitable **abstract grammar**.

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Objectives:

Guiding objectives

In the lecture:

The objectives are explained.

A strategy for grammar development

1. **Examples**: Write at least one example for every intended language construct. Keep the examples for checking the grammar and the parser.
2. **Sub-grammars**: Decompose a non-trivial task into topics covered by sub-gammars, e.g. statements, declarations, expressions, over-all structure.
3. **Top-down**: Begin with the start symbol of the (sub-)grammar, and refine each nonterminal according to steps 4 - 7 until all nonterminals of the (sub-)grammar are refined.
4. **Alternatives**: Check whether the language construct represented by the current nonterminal, say Statement, shall occur in structurally different alternatives, e.g. while-statement, if-statement, assignment. Either introduce chain productions, like
   `Statement ::= WhileStatement | IfStatement | Assignment.`
   or apply steps 5 - 7 for each alternative separately.
5. **Consists of**: For each (alternative of a) nonterminal representing a language construct explain its immediate structure in words, e.g. „A Block is a declaration sequence followed by a statement sequence, both enclosed in curly braces." Refine only one structural level. Translate the description into a production. If a sub-structure is not yet specified introduce a new nonterminal with a speaking name for it, e.g.
   `Block ::= '{' DeclarationSeq StatementSeq '}'.`
6. **Natural structure**: Make sure that step 5 yields a „natural" structure, which supports notions used for static or dynamic semantics, e.g. a range for valid bindings.
7. **Useful patterns**: In step 5 apply patterns for description of sequences, expressions, etc.

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Objectives:

Develop CFGs systematically

In the lecture:

- Apply the strategy for a little task.
- Apply the strategy in context of the running project.
- Apply the patterns of slides GPS-2.10, GPS-2.10, 12, 14, 15.
- The strategy is applicable for the concrete and the abstract syntax.

Suggested reading:

Kastens / Übersetzerbau, Section 4.1

Suggested reading:

slide GdP-2.10ff

Grammar design for an existing language

- Take the grammar of the **language specification literally**.
- Only **conservative modifications** for parsability or for mapping to abstract syntax.
- **Describe all modifications**.
  (see ANSI C Specification in the Eli system description
  http://www.uni-paderborn.de/fachbereich/AG/agkastens/eli/examples/eli_cE.html)

  - **Java** language specification (1996):
    Specification grammar is not LALR(1).
    5 problems are described and how to solve them.
  - **Ada** language specification (1983):
    Specification grammar is LALR(1)
    - requirement of the language competition
  - **ANSI C, C++**:
    several ambiguities and LALR(1) conflicts, e.g.
    „**dangling else**",
    „**typedef problem**":
    `A (*B);`
    is a declaration of variable **`B`**, if **`A`** is a type name,
    otherwise it is a call of function **`A`**

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Objectives:

Avoid document modifications

In the lecture:

- Explain the conservative strategy.
- Java gives a solution for the dangling else problem.
- For typedef problem see PLaC-2.3.

Grammar design together with language design

Read grammars before writing a new grammar.

Apply **grammar patterns systematically** (cf. GPS-2.5, GPS-2.8)

- repetitions
- optional constructs
- precedence, associativity of operators

Syntactic structure should reflect semantic structure:

E. g. a range in the sense of scope rules should be represented by a single subtree of the derivation tree (of the abstract tree).

Violated in Pascal:

functionDeclaration ::= functionHeading block
functionHeading ::= ‘function‘ identifier formalParameters ‘:‘ resultType ‘;‘

formalParameters together with block form a range,
but identifier does not belong to it

Objectives:

Grammar design rules

In the lecture:

- Refer to GdP slides.
- Explain semantic structure.
- Show violation of the example.

Syntactic restrictions versus semantic conditions

Express a restriction **syntactically** only if
it can be **completely covered with reasonable complexity**:

- **Restriction can not be decided syntactically**:
  e.g. type check in expressions:
  BoolExpression ::= IntExpression ‘<‘ IntExpression

- **Restriction can not always be decided syntactically**:
  e. g. disallow array type to be used as function result
  Type ::= ArrayType | NonArrayType | Identifier
  ResultType ::= NonArrayType
  If a type identifier may specify an array type,
  a semantic condition is needed, anyhow

- **Syntactic restriction is unreasonably complex**:
  e. g. distinction of compile-time expressions from ordinary expressions requires duplication of the expression syntax.

Objectives:

How to express restrictions

In the lecture:

- Examples are explained.
- Semantic conditions are formulated with attribute grammar concepts, see next chapter.

Assignments:

Discuss further examples for restrictions.

Eliminate ambiguities

unite syntactic constructs - distinguish them semantically

Examples:

- Java:
```
ClassOrInterfaceType   ::= ClassType | InterfaceType
InterfaceType          ::= TypeName
ClassType              ::= TypeName
```
  replace first production by
```
ClassOrInterfaceType   ::= TypeName
```
  semantic analysis distinguishes between class type and interface type

- Pascal:
```
factor               ::= variable | ... | functionDesignator
variable             ::= entireVariable | ...
entireVariable       ::= variableIdentifier
variableIdentifier   ::= identifier                                      (**)
functionDesignator   ::= functionIdentifier                              (*)
                     |   functionIdentifer '(' actualParameters ')'
functionIdentifier   ::= identifier
```
  eliminate marked (*) alternative
  semantic analysis checks whether (**) is a function identifier

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Objectives:

Typical ambiguities

In the lecture:

- Same notation with different meanings;
- ambiguous, if they occur in the same context.
- Conflicting notations may be separated by several levels of productions (Pascal example)

Questions:

Unbounded lookahead

The decision for a **reduction** is determined by a **distinguishing token** that may be **arbitrarily far to the right**:

Example, **forward** declarations as could have been defined in Pascal:

```
functionDeclaration ::=
        'function' forwardIdent formalParameters ':' resultType ';' 'forward'

      | 'function' functionIdent formalParameters ':' resultType ';' block
```

The distinction between **forwardIdent** and **functionIdent** would require to see the **forward** or the **begin** token.

Replace **forwardIdent** and **functionIdent** by the same nonterminal; distinguish semantically.

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Objectives:

Typical situation

In the lecture:

Explain the problem and the solution using the example

Questions:

3.3 Recursive descent parser

top-down (construction of the **derivation** tree), **predictive** method

Systematic transformation of a context-free grammar into a set of functions:

non-terminal symbol X	function X
alternative productions for X	branches in the function body
decision set of production p_i	decision for branch p_i
non-terminal occurrence X ::= ... Y ...	function call Y()
terminal occurrence X ::= ... t ...	accept a token t and read the next token

Productions for `Stmt`:

```
p1: Stmt ::=
      Variable ':=' Expr

p2: Stmt ::=
      'while' Expr 'do' Stmt
```

```
void Stmt ()
{  switch (CurrSymbol)
   {
     case decision set for p1:
        Variable();
        accept(assignSym);
        Expr();
        break;
     case decision set for p2:
        accept(whileSym);
        Expr();
        accept(doSym);
        Stmt();
        break;
   default: Fehlerbehandlung();
}  }
```


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Objectives:

Understand the construction schema

In the lecture:

Explanation of the method:

- Demonstrate the construction of a left-derivation and the top-down construction of a derivation tree by this animation.
- Relate grammar constructs to function constructs.
- Each function plays the role of an acceptor for a symbol.
- accept function for reading and checking of the next token (scanner).
- Computation of decision sets on PLaC-3.6.
- Decision sets must be pairwise disjoint!

Suggested reading:

Kastens / Übersetzerbau, Section 4.2

Questions:

- A parser algorithm is based on a stack automaton. Where is the stack of a recursive descent parser? What corresponds to the states of the stack automaton?
- Where can actions be inserted into the functions to output production sequences in postfix or in prefix form?

Grammar conditions for recursive descent

Definition: A context-free grammar is **strong LL(1)**, if for any pair of **productions** that have the **same symbol on their left-hand sides**, A ::= u and A ::= v, the **decision sets are disjoint**:

DecisionSet (A ::= u) $\cap$ **DecisionSet (A ::= v) =** $\emptyset$

with

DecisionSet (A ::= u) := if nullable (u) then **First (u)** $\cup$ **Follow (A)** else **First (u)**

nullable (u) holds iff a derivation u $\Rightarrow^*$ ε exists

First (u) := { t ∈ T | v ∈ V* exists and a derivation u $\Rightarrow^*$ t v }

Follow (A):= { t ∈ T | u,v ∈ V* exist, A ∈ N and a derivation S $\Rightarrow^*$ u A t v }

Example:

	production			DecisionSet
p1:	Prog	::=	Block #	**begin**
p2:	Block	::=	**begin** Decls Stmts **end**	**begin**
p3:	Decls	::=	Decl **;** Decls	**new**
p4:	Decls	::=		Ident **begin**
p5:	Decl	::=	**new** Ident	**new**
p6:	Stmts	::=	Stmts **;** Stmt	**begin** Ident
p7:	Stmts	::=	Stmt	**begin** Ident
p8:	Stmt	::=	Block	**begin**
p9:	Stmt	::=	Ident **:=** Ident	Ident

non-terminal

X	First (X)	Follow (X)
Prog	**begin**	
Block	**begin**	**# ; end**
Decls	**new**	Ident **begin**
Decl	**new**	**;**
Stmts	**begin** Ident	**; end**
Stmt	**begin** Ident	**; end**

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Objectives:

Strong LL(1) can easily be checked

In the lecture:

- Explain the definitions using the example.
- First set: set of terminal symbols, which may begin some token sequence that is derivable from u.
- Follow set: set of terminal symbols, which may follow an A in some derivation.
- Disjoint decision sets imply that decisions can be made deterministically using the next input token.
- For k=1: Strong LL(k) is equivalent to LL(k).

Suggested reading:

Kastens / Übersetzerbau, Section 4.2, LL(k) conditions, computation of First sets and Follow sets

Questions:

The example grammar is not strong LL(1).

- Show where the condition is violated.
- Explain the reason for the violation.
- What would happen if we constructed a recursive descent parser although the condition is violated?

Computation rules for nullable, First, and Follow

Definitions:

nullable(u) holds iff a derivation $u \Rightarrow^* \varepsilon$ exists

First(u):= $\{ t \in T \mid v \in V^*$ exists and a derivation $u \Rightarrow^* t\ v \}$

Follow(A):= $\{ t \in T \mid u,v \in V^*$ exist, $A \in N$ and a derivation $S \Rightarrow^* u\ A\ v$ such that $t \in First(v) \}$

with G = (T, N, P, S); $V = T \cup N$; $t \in T$; $A \in N$; $u,v \in V^*$

Computation rules:

nullable(ε) = true; nullable(t) = false; nullable(uv) = nullable(u) $\wedge$ nullable(v);
nullable(A) = true iff $\exists$ A::=u $\in$ P $\wedge$ nullable(u)

First(ε) = ∅; First(t) = {t};
First(uv) = if nullable(u) then First(u) $\cup$ First(v) else First(u)
First(A) = First(u_1) $\cup ... \cup$ First(u_n) for all A::=$u_i \in$ P

Follow(A):
if A=S then # $\in$ Follow(A)
if Y::=uAv $\in$ P then First(v) $\subseteq$ Follow(A) and if nullable(v) then Follow(Y) $\subseteq$ Follow(A)

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Objectives:

Compute First- and Follow-sets

In the lecture:

- Explain and apply computation rules

Suggested reading:

Kastens / Übersetzerbau, Section 4.2, LL(k) conditions, computation of First sets and Follow sets

Grammar transformations for LL(1)

Consequences of strong LL(1) condition:
A strong LL(1) grammar can not have

Simple **grammar transformations** that keep the defined **language invariant**:

- **alternative productions that begin with the same symbols:**

left-factorization:

non-LL(1) productions	transformed
A ::= v u	A ::= v X
A ::= v w	X ::= u
	X ::= w

- **productions that are directly or indirectly left-recursive:**

elimination of direct recursion:

A ::= A u	A ::= v X
A ::= v	X ::= u X
	X ::=

special case empty v:

A ::= A u	A ::= u A
A ::=	A ::=

$u, v, w \in V^*$
$X \in N$ does not occur in the original grammar

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Objectives:

Understand transformations and their need

In the lecture:

- Argue why strong LL(1) grammars can not have such productions.
- Show why the transformations remove those problems.
- Replacing left-recursion by right recursion would usually distort the structure.
- There are more general rules for indirect recursion.

Questions:

- Apply recursion elimination for expression grammars.

LL(1) extension for EBNF constructs

EBNF constructs can avoid violation of strong LL(1) condition:

EBNF construct:	**Option [u]**	**Repetition (u)***
Production:	A ::= v [u] w	A ::= v (u)* w

additional LL(1)-condition:

if nullable(w)
then First(u) ∩ (First(w) ∪ Follow(A)) = ∅
else First(u) ∩ First(w) = ∅

in recursive descent parser:

Option	Repetition
v if (CurrToken in First(u)) { u } w	v while (CurrToken in First(u)) { u } w

Repetition (u)+ left as exercise

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Objectives:

Understand transformations and their need

In the lecture:

- Show EBNF productions in recursive descent parsers.

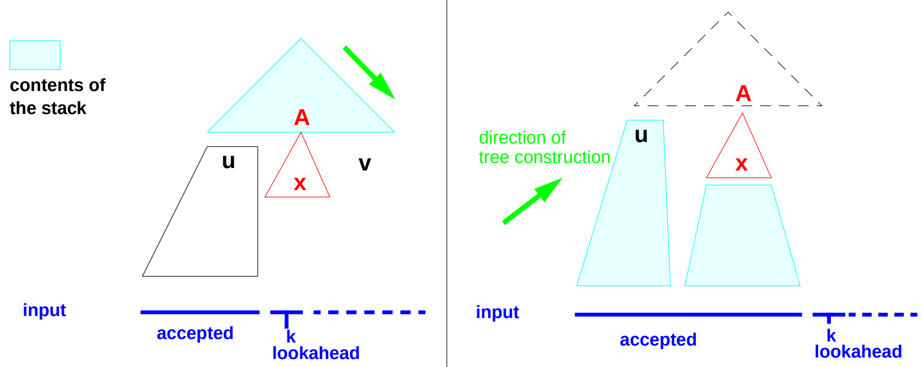
Questions:

- Write a strong LL(1) expression grammar using EBNF.

Comparison: top-down vs. bottom-up

Information a stack automaton has when it decides to apply production A ::= x :

top-down, predictive leftmost derivation	**bottom-up rightmost derivation backwards**



A bottom-up parser has seen more of the input when it decides to apply a production.

Consequence: **bottom-up** parsers and their grammar classes are more **powerful**.

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Objectives:

Understand the decision basis of the automata

In the lecture:

Explain the meaning of the graphics:

- role of the stack: contains states of the automaton,
- accepted input: will not be considered again,
- lookahead: the next k symbols, not yet accepted
- leftmost derivation: leftmost non-terminal is derived next; rightmost correspondingly,
- consequences for the direction of tree construction,

Abbreviations

- LL: (L)eft-to-right, (L)eftmost derivation,
- LR: (L)eft-to-right, (R)ightmost derivation,
- LALR: (L)ook(A)head LR

Suggested reading:

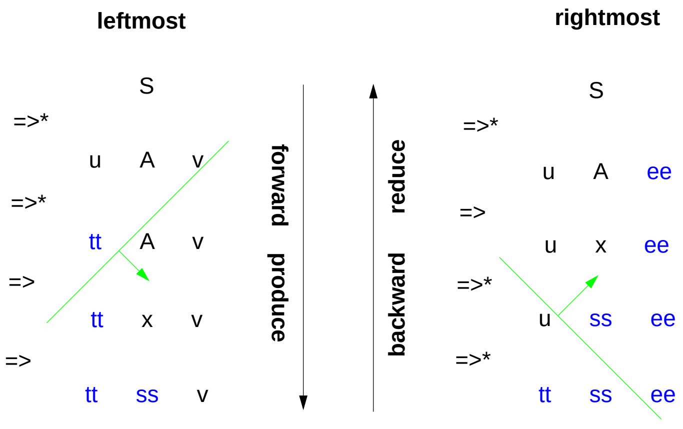
Kastens / Übersetzerbau, Section Text zu Abb. 4.2-1, 4.3-1

Questions:

Use the graphics to explain why a bottom-up parser without lookahead (k=0) is reasonable, but a top-down parser is not.

PLaC-3.9

Leftmost and rightmost derivations



u, v, x ∈ V*

tt, ss, ee ∈ T*

A ∈ N

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Objectives:

Understand rightmost derivation backward

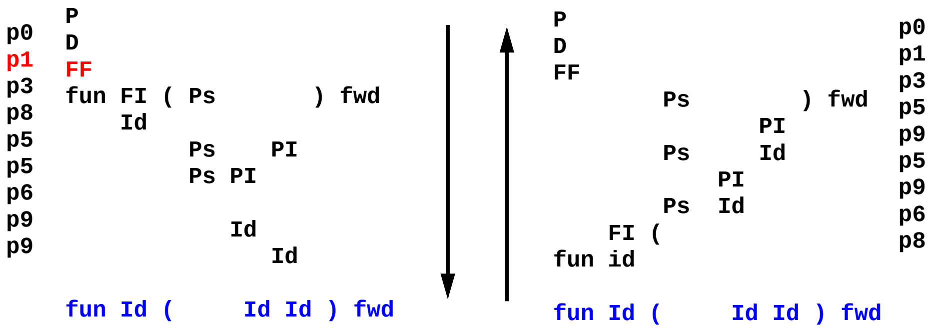
In the lecture:

- Explain the two derivation patterns.

PLaC-3.9a

Derivation tree: top-down vs. bottom-up construction

```
p0:  P  ::= D
P1:  D  ::= FF
P2:  D  ::= FB
P3:  FF ::= 'fun' FI '(' Ps ')' 'fwd'
P4:  FB ::= 'fun' FI '(' Ps ')' B
P5:  Ps ::= Ps PI
P6:  Ps ::=
p7:  B  ::= '{' '}'
p8:  FI ::= Id
p9:  PI ::= Id
```



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Objectives:

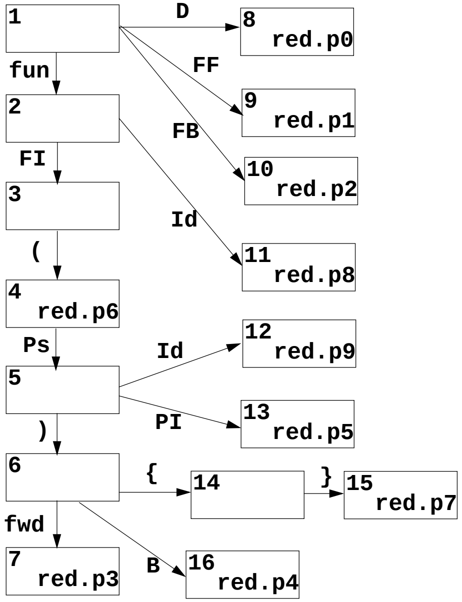
Understand derivation tree construction

In the lecture:

Use this animation to explain

- On the left: construction of a left-derivation.
- The magenta production names indicate that the decision can not be made on the base of the derivation so far and the next input tokens.
- On the right: construction of a derivation backward (bottom-up).
- No decision problem occurs.
- It is a right-derivation constructed backward.

LR(0) -Automaton



reduction	stack	input
	1	fun Id(Id Id)fwd
	1 2	Id(Id Id)fwd
p8	1 2 11	(Id Id)fwd
	1 2 3	(Id Id)fwd
p6	1 2 3 4	Id Id)fwd
	1 2 3 4 5	Id Id)fwd
p9	1 2 3 4 5 12	Id)fwd
p5	1 2 3 4 5 13	Id)fwd
	1 2 3 4 5	Id)fwd
p9	1 2 3 4 5 12	)fwd
p5	1 2 3 4 5 13	)fwd
	1 2 3 4 5	)fwd
	1 2 3 4 5 6	fwd
p3	1 2 3 4 5 6 7	#
p1	1 9	#
p0	1 8	#

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Objectives:

Understand understand how LR automata work

In the lecture:

- See PLaC-3.12 for explanations of the operations shift and reduce.
- Execute the automaton.

3.4 LR parsing

LR(k) grammars introduced 1965 by Donald Knuth; non-practical until subclasses were defined.

LR parsers construct the derivation tree **bottom-up,** a right-derivation backwards.

LR(k) grammar condition can not be checked directly, but
a context-free grammar is LR(k), iff the (canonical) **LR(k) automaton is deterministic**.

We consider only **1 token lookahead: LR(1).**

Comparison of LL and LR states:

The **stacks** of LR(k) and LL(k) automata **contain states**.

The construction of LR and LL states is based on the notion of **items** (see next slide).

Each **state** of an automaton represents **LL: one item** **LR: a set of items**
An LL item corresponds to a position in a case branch of a recursive function.

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Objectives:

Introduction

In the lecture:

- Explain the comparison.

LR(1) items

An **item** represents the progress of analysis with respect to one production:

[A ::= u . v   R]   **e. g. [B ::= (. D ; S)   {#}]**

. marks the position of analysis: *accepted and reduced* . *to be accepted*

R expected **right context:**
a **set of terminals** which may follow in the input
when the complete production is accepted.
(general k>1: R contains sequences of terminals not longer than k)

Items can distinguish different right contexts: [A ::= u . v R] and [A ::= u . v R']

Reduce item:

[A ::= u v .   R]   **e. g. [B ::= (D ; S) .   {#}]**

characterizes a reduction using this production if the next input token is in R.

The automaton uses R only for the decision on reductions!

A **state** of an LR automaton represents **a set of items**

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Objectives:

Fundamental notions of LR automata

In the lecture:

Explain

- items are also called situations,
- meaning of an item,
- lookahead in the input and right context in the automaton.
- There is no right context set in case of an LR(0) automaton.

Suggested reading:

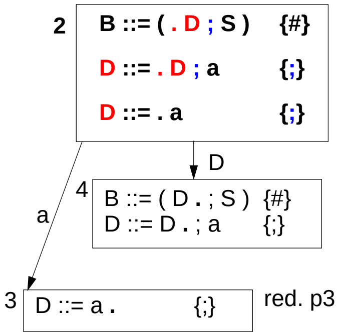
Kastens / Übersetzerbau, Section 4.3

Questions:

- What contains the right context set in case of a LR(3) automaton?

LR(1) states and operations

A **state of an LR automaton represents a set of items**
Each item represents a way in which analysis may proceed from that state.



A shift transition is made under
a **token read** from input or
a **non-terminal** symbol
obtained from a **preceding reduction.**
The state is pushed.

A **reduction** is made according to a reduce item.
n states are popped for a production of length n.

Operations:

shift	read and push the next state on the stack
reduce	reduce with a certain production, pop n states from the stack
error	error recognized, report it, recover
stop	input accepted

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Objectives:

Understand LR(1) states and operations

In the lecture:

Explain

- Sets of items,
- shift transitions,
- reductions.

Suggested reading:

Kastens / Übersetzerbau, Section 4.3

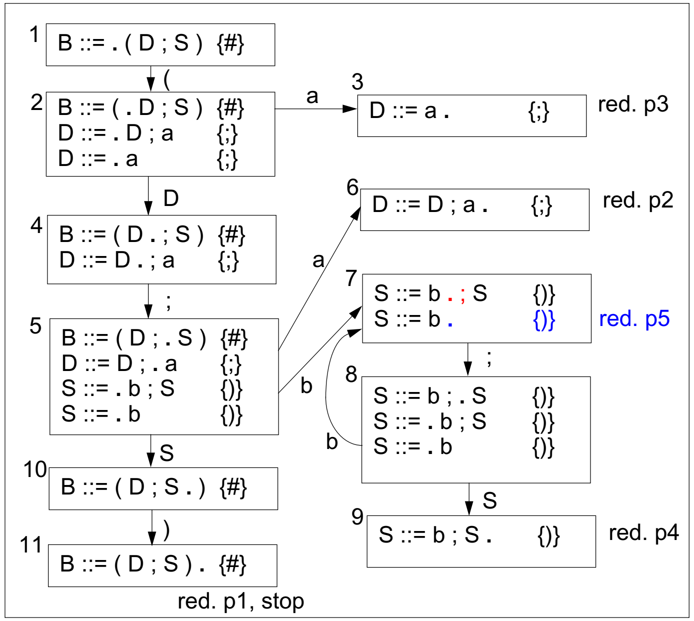
Questions:

- Explain: A state is encoded by a number. A state represents complex information which is important for construction of the automaton.

Example for a LR(1) automaton

Grammar:

p1 B ::= (D ; S)
p2 D ::= D ; a
p3 D ::= a
p4 S ::= b ; S
p5 S ::= b



In state 7 a decision is required on next input:

- if ; then shift
- if) then reduce p5

In states 3, 6, 9, 11 a decision is not required:

- reduce on any input

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Objectives:

Example for states, transitions, and automaton construction

In the lecture:

Use the example to explain

- the start state,
- the creation of new states,
- transitions into successor states,
- transitive closure of item set,
- push and pop of states,
- consequences of left-recursive and right-recursive productions,
- use of right context to decide upon a reduction,

erläutern.

Suggested reading:

Kastens / Übersetzerbau, Section 4.3

Questions:

- Describe the subgraphs for left-recursive and right-recursive productions. How do they differ?
- How does a LR(0) automaton decide upon reductions?

Construction of LR(1) automata

Algorithm: 1. Create the start state.
2. For each created state compute the transitive closure of its items.
3. Create transitions and successor states as long as new ones can be created.

Transitive closure is to be applied to each state q:
Consider all items in q with the analysis position before a non-terminal B:
[A_1 ::= u_1 . B v_1 R_1] ... [A_n ::= u_n . B v_n R_n],
then for each production **B ::= w**
[B ::= . w First (v_1 R_1)∪...∪First (v_n R_n)]
has to be added to state q.

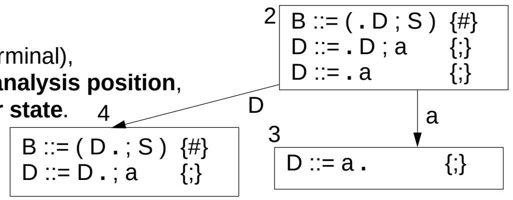
before: 2 B ::= (. D ; S) {#}

after: 2 B ::= (. D ; S) {#}
D ::= . D ; a {;}∪{;}
D ::= . a {;}∪{;}

Start state:
Closure of **[S ::= . u {#}]**
S ::= u is the **unique start production**,
is an **(artificial) end symbol** (eof)

1 B ::= . (D ; S) {#}

Successor states:
For each **symbol x** (terminal or non-terminal), which occurs in some items **after the analysis position**, a **transition** is created **to a successor state**. That contains corresponding items with the **analysis position advanced behind the x** occurrence.



Lecture Programming Languages and Compilers WS 2013/14 / Slide 314

Objectives:

Understand the method

In the lecture:

Explain using the example on PLaC-3.13:

- transitive closure,
- computation of the right context sets,
- relation between the items of a state and those of one of its successor

Suggested reading:

Kastens / Übersetzerbau, Section 4.3

Questions:

- Explain the role of the right context.
- Explain its computation.

Operations of LR(1) automata

shift x (terminal or non-terminal):
from current state q
under x into the **successor state q‘** ,
push q‘

reduce p:
apply production p B ::= u ,
pop as many states,
as there are **symbols in u**, from the
new current state make a **shift with B**

error:
the current state has no transition
under the next input token,
issue a **message** and **recover**

stop:
reduce start production,
see # in the input

Example:

stack	input	reduction
1	(a ; a ; b ; b) #	
1 2	a ; a ; b ; b) #	
1 2 3	; a ; b ; b) #	p3
1 2	; a ; b ; b) #	
1 2 4	; a ; b ; b) #	
1 2 4 5	a ; b ; b) #	
1 2 4 5 6	; b ; b) #	p2
1 2	; b ; b) #	
1 2 4	; b ; b) #	
1 2 4 5	b ; b) #	
1 2 4 5 7	; b) #	
1 2 4 5 7 8	b) #	
1 2 4 5 7 8 7	) #	p5
1 2 4 5 7 8	) #	
1 2 4 5 7 8 9	) #	p4
1 2 4 5	) #	
1 2 4 5 10	) #	
1 2 3 5 10 11	#	p1
1	#	

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Objectives:
Understand how the automaton works

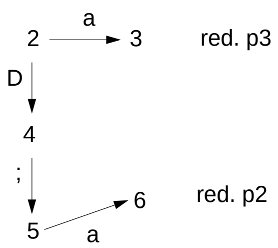
In the lecture:
Explain operations

Questions:
- Why does the automaton behave differently on a-sequences than on b-sequences?
- Which behaviour is better?

Left recursion versus right recursion

left recursive productions:

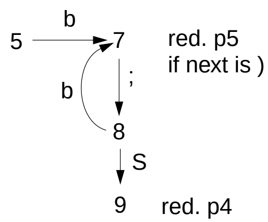
p2: D ::= D ; a
p3: D ::= a



reduction immediately after
each **; a** is accepted

right recursive productions:

p4: S ::= b ; S
p5: S ::= b



the states for all **; b** are
pushed before the first reduction

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Objectives:
Understand the difference

In the lecture:
Explain
- why right recursion fills the stack deeply,
- why left recursion is advantagous.

LR conflicts

An **LR(1) automaton that has conflicts is not deterministic**.
Its **grammar is not LR(1)**;
correspondingly defined for any other LR class.

2 kinds of conflicts:

reduce-reduce conflict:
A state contains two reduce items, the **right context sets** of which are **not disjoint**:

```
...
A ::= u .   R1
B ::= v .   R2
...
```

R1, R2 not disjoint

shift-reduce conflict:
A state contains
a **shift item** with the **analysis position in front of a t** and
a **reduce item with t in its right context set**.

```
...
A ::= u .t v   R1
B ::= w .      R2
...
```

t ∈ R2

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Objectives:

Understand LR conflicts

In the lecture:

Explain: In certain situations the given input token t can not determine

- Reduce-reduce: which reduction is to be taken;
- Shift-reduce: whether the next token is to be shifted, a reduction is to be made.

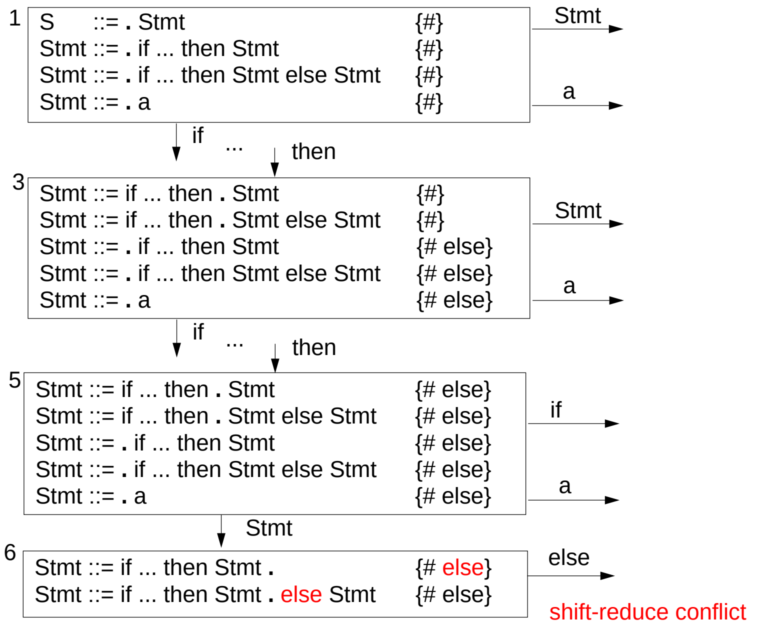
Suggested reading:

Kastens / Übersetzerbau, Section 4.3

Questions:

- Why can a shift-shift conflict not exist?
- In LR(0) automata items do not have a right-context set. Explain why a state with a reduce item may not contain any other item.

Shift-reduce conflict for „dangling else“ ambiguity



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Objectives:

See a conflict in an automaton

In the lecture:

Explain

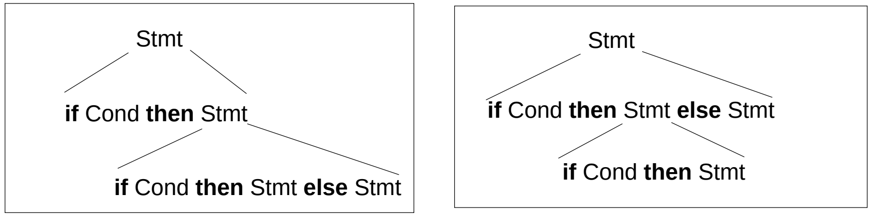
- the construction
- a solution of the conflict: The automaton can be modified such that in state 6, if an else is the next input token, it is shifted rather than a reduction is made. In that case the ambiguity is solved such that the else part is bound to the inner if. That is the structure required in Pascal and C. Some parser generators can be instructed to resolve conflicts in this way.

Suggested reading:

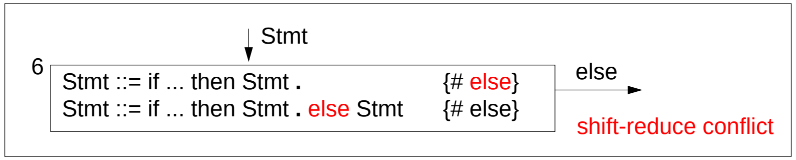
Kastens / Übersetzerbau, Section 4.3

Decision of ambiguity

dangling else ambiguity:



desired solution for Pascal, C, C++, Java



State 6 of the automaton can be modified such that
an input token **else is shifted** (instead of causing a reduction);
yields the desired behaviour.

Some parser generators allow such modifications.

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Objectives:

Understand modification of automaton

In the lecture:

Explain why the desired effect is achieved.

Simplified LR grammar classes

LR(1):

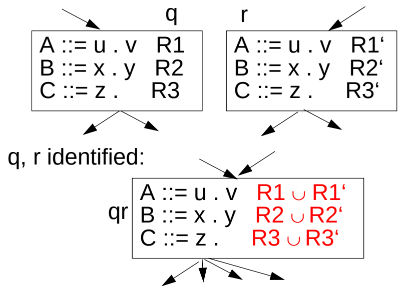
too many states for practical use**,** because right-contexts distinguish many states.
Strategy: simplify right-contexts sets; **fewer states**; grammar classes less powerful

LALR(1):

construct LR(1) automaton,
identify LR(1) states if their items
differ only in their right-context sets,
unite the sets for those items;

yields the states of the **LR(0) automaton**
augmented by the "exact" LR(1) right-context.

State-of-the-art parser generators accept LALR(1)



SLR(1):

LR(0) states; in reduce items
use larger right-context sets for decision:
[A ::= u . Follow (A)]

A ::= u . v
B ::= x . y
C ::= z . Follow(C)

LR(0):

all items **without right-context**
Consequence: reduce items only in singleton sets

C ::= z .

Lecture Programming Languages and Compilers WS 2013/14 / Slide 320

Objectives:

Understand relations between LR classes

In the lecture:

Explain:

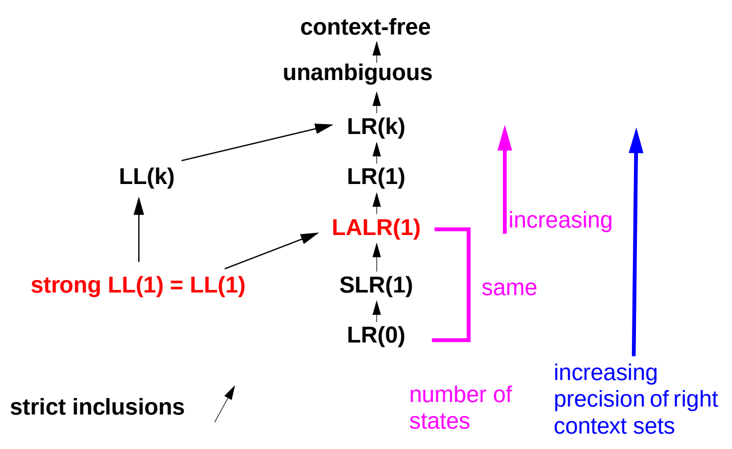
- LALR(1), SLR(1), LR(0) automata have the same number of states,
- compare their states,
- discuss the grammar classes for the example on slide PLaC-3.13.

Suggested reading:

Kastens / Übersetzerbau, Section 4.3

Questions:

Hierarchy of grammar classes



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Objectives:

Understand the hierarchy

In the lecture:

Explain:

- the reasons for the strict inclusions,

Suggested reading:

Kastens / Übersetzerbau, Section 4.3

Questions:

- Assume that the LALR(1) construction for a given grammar yields conflicts. Classify the potential reasons using the LR hierarchy.

Reasons for LALR(1) conflicts

Grammar condition does not hold:

Class	Reason	Frequency
context-free	**ambiguous**	most cases
unambiguous	**unbounded lookahead** needed	
LR(k)	**fixed length lookahead > 1** needed	
LR(1)	**merge of LR(1) states** introduces **conflicts**	rare cases
LALR(1)		

LALR(1) parser generator can not distinguish these cases.

Lecture Programming Languages and Compilers WS 2013/14 / Slide 321a

Objectives:

Distinguish cases

In the lecture:

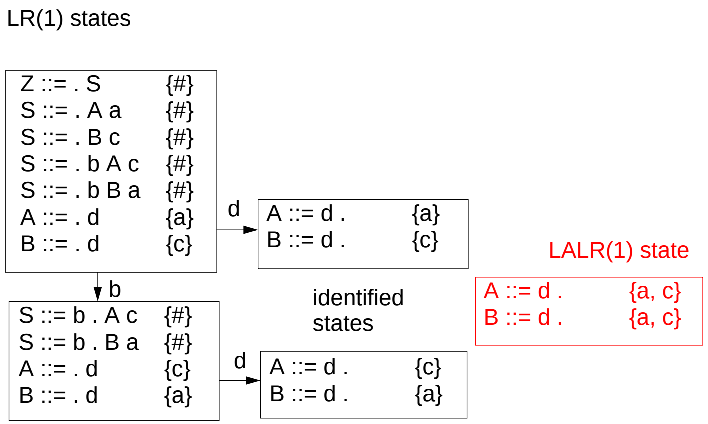
The cases are explained.

LR(1) but not LALR(1)

Identification of LR(1) states causes non-disjoint right-context sets.

Artificial example:

Grammar:
Z ::= S
S ::= A a
S ::= B c
S ::= b A c
S ::= b B a
A ::= d.
B ::= d.



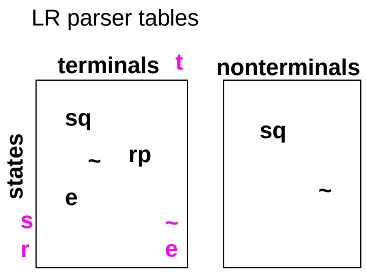
Avoid the distinction between A and B - at least in one of the contexts.

Lecture Programming Languages and Compilers WS 2013/14 / Slide 321b

Objectives:
Understand source of conflicts

In the lecture:
Explain the pattern, and why identification of states causes a conflict.

Table driven implementation of LR automata



sq: shift into state q

rp: reduce production p

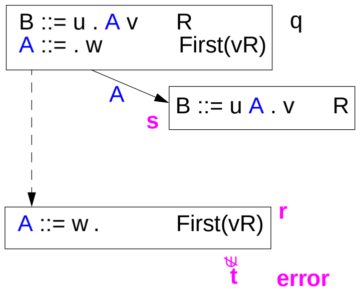
e: error

~: not reachable
don't care

nonterminal table

- has **no reduce entries** and **no error entries** (only **shift** and **don't-care** entries)
  reason:
  a reduction to A reaches a state from where a shift under A exists (by construction)

unreachable entries in terminal table:
if **t** is erroneus input in state **r**, then state **s** will not be reached with input **t**



Lecture Programming Languages and Compilers WS 2013/14 / Slide 322

Objectives:
Understand properties of LR tables

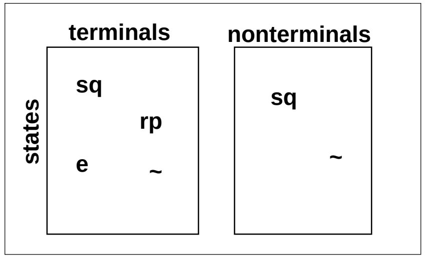
In the lecture:
Explanation of

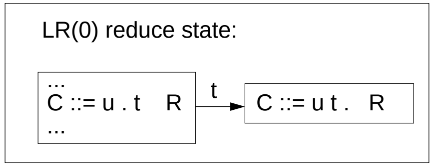
- pair of tables and their entries,
- unreachable entries,

Questions:

- Why are there no error entries in the nonterminal part?
- Why are there unreachable entries?

Implementation of LR automata





Compress tables:

- **merge rows or columns** that differ only in irrelevant entries; method: graph coloring
- extract a **separate error matrix** (bit matrix); increases the chances for merging
- **normalize the values of rows or columns**; yields smaller domain; supports merging
- **eliminate LR(0) reduce states**; new operation in predecessor state: **shift-reduce** eliminates about 30% of the states in practical cases

About 10-20% of the original table sizes can be achieved!

Directly programmed LR-automata are possible - but usually too large.

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Objectives:

Implementation of LR tables

In the lecture:

Explanation of

- compression techniques, derived from general table compression,
- Singleton reduction states yield an effective optimization.

Questions:

- Why are there no error entries in the nonterminal part?
- Why are there unreachable entries?
- Why does a parser need a shift-reduce operation if the optimization of LR(0)-reduction states is applied?

Parser generators

PGS	Univ. Karlsruhe; in Eli	**LALR(1), table-driven**
Cola	Univ. Paderborn; in Eli	**LALR(1), optional: table-driven or directly programmed**
Lalr	Univ. / GMD Karlsruhe	**LALR(1), table-driven**
Yacc	Unix tool	**LALR(1), table-driven**
Bison	Gnu	**LALR(1), table-driven**
Llgen	Amsterdam Compiler Kit	**LL(1), recursive descent**
Deer	Univ. Colorado, Bouder	**LL(1), recursive descent**

Form of grammar specification:
EBNF: Cola, PGS, Lalr; **BNF**: Yacc, Bison

Error recovery:

simulated continuation, automatically generated:	Cola, PGS, Lalr
error productions, hand-specified:	Yacc, Bison

Actions:

statements in the implementation language	
at the end of productions:	Yacc, Bison
anywhere in productions:	Cola, PGS, Lalr

Conflict resolution:

modification of states (reduce if ...)	Cola, PGS, Lalr
order of productions:	Yacc, Bison
rules for precedence and associativity:	Yacc, Bison

Implementation languages:
C: Cola, Yacc, Bison **C, Pascal, Modula-2, Ada**: PGS, Lalr

Lecture Programming Languages and Compilers WS 2013/14 / Slide 324

Objectives:

Overview over parser generators

In the lecture:

- Explain the significance of properties

Suggested reading:

Kastens / Übersetzerbau, Section 4.5

3.5 Syntax Error Handling
General criteria

- **recognize error as early as possible**
  LL and LR can do that:
  no transitions after error position
- **report the symptom in terms of the source text**
  rather than in terms of the state of the parser
- **continue parsing short after the error position**
  analyze as much as possible
- **avoid avalanche errors**
- **build a tree that has a correct structure**
  later phases must not break
- **do not backtrack, do not undo actions,**
  not possible for semantic actions
- **no runtime penalty for correct programs**

Lecture Programming Languages and Compilers WS 2013/14 / Slide 325

Objectives:

Accept strong requirements

In the lecture:

- The reasons for and the consequences of the requirements are discussed.
- Some of the requirements hold for error handling in general - not only that of the syntactic analysis.

Error position

Error recovery: Means that are taken by the parser after recognition of a syntactic error in order to continue parsing

Correct prefix: The token sequence $w \in T^*$ is a correct prefix in the language L(G), if there is an $u \in T^*$ such that **w u** $\in$ **L(G)**; i. e. w can be extended to a sentence in L(G).

Error position: t is the (first) error position in the **input w t x** , where $t \in T$ and w, $x \in T^*$, if **w is a correct prefix** in L(G) and **w t is not a correct prefix**.

Example:

```
int compute (int i) { a = i * / c; return i;}
```

w = `int compute (int i) { a = i *`, t = `/`

LL and LR parsers recognize an error at the error position; they can not accept t in the current state.

Lecture Programming Languages and Compilers WS 2013/14 / Slide 326

Objectives:

Error position from the view of the parser

In the lecture:

Explain the notions with respect to parser actions using the examples.

Questions:

Assume the programmer omitted an opening parenthesis.

- Where is the error position?
- What is the symptom the parser recognizes?

Error recovery

Continuation point:
A token d at or behind the error position t such that **parsing of the input continues at d**.

Error repair
with respect to a consistent derivation
- regardless the intension of the programmer!

Let the input be w t x with the error position at t and let w t x = w y d z, then the recovery (conceptually) **deletes y** and **inserts v**, such that **w v d is a correct prefix** in L(G), with d ∈ T and w, y, v, z ∈ T*.

error position
↓
w t x =
w y d z
w v d z
↑
continuation

Examples:

`w` `y d` `z`	`w` `yd` `z`	`w` `y d z`
`a = i * / c;...`	`a = i * / c;...`	`a = i * / c;...`
`a = i *   c;...`	`a = i *e/ c;...`	`a = i * e  ;...`
delete `/`	**insert** error identifier e	**delete** `/ c` and **insert** error id. **e**

Lecture Programming Languages and Compilers WS 2013/14 / Slide 327

Objectives:
Understand error recovery

In the lecture:
Explain the notions with respect to parser actions using the examples.

Questions:
Assume the programmer omitted an opening parenthesis.

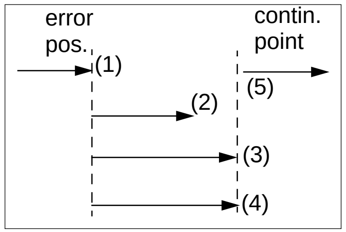
- What could be a suitable repair?

Recovery method: simulated continuation

Problem: Determine a continuation point close to the error position and reach it.
Idea: Use parse stack to determine a set D of tokens as potential continuation points.

Steps of the method:

1. **Save the contents of the parse stack** when an error is recognized.
2. **Compute a set D ⊆ T of tokens that may be used as continuation point** (**anchor set**)
   Let a modified parser run to completion:
   Instead of reading a token from input it is inserted into D; (modification given below)
3. **Find a continuation point d**: Skip input tokens until a token of D is found.
4. **Reach the continuation point d**:
   Restore the saved parser stack as the current stack.
   Perform dedicated transitions until d is acceptable.
   Instead of reading tokens (conceptually) insert tokens.
   Thus a correct prefix is constructed.
5. **Continue normal parsing**.



Augment parser construction for steps 2 and 4:
For each parser state select a transition and its token, such that the parser empties its stack and terminates as fast as possible.
This selection can be **generated automatically**.
The quality of the recovery can be improved by deletion/insertion of elements in D.

Lecture Programming Languages and Compilers WS 2013/14 / Slide 328

Objectives:
Error recovery can be generated

In the lecture:

- Explain the idea and the steps of the method.
- The method yields a correct parse for any input!
- Other, less powerful methods determine sets D statically at parser construction time, e. g. semicolon and curly bracket for errors in statements.

Questions:

- How does this method fit to the general requirements for error handling?

4. Attribute grammars and semantic analysis

Input: **abstract program tree**

Tasks:	**Compiler module:**
name analysis	environment module
properties of program entities	definition module
type analysis, operator identification	signature module

Output: **attributed program tree**

Standard implementations and generators for compiler modules

Operations of the compiler modules are called at nodes of the abstract program tree

Model: dependent computations in trees

Specification: **attribute grammars**

generated: a **tree walking algorithm** that calls functions of semantic modules **in specified contexts** and in an **admissible order**

Lecture Programming Languages and Compilers WS 2013/14 / Slide 401

Objectives:

Tasks and methods of semantic analysis

In the lecture:

Explanation of the

- tasks,
- compiler modules,
- principle of dependent computations in trees.

Suggested reading:

Kastens / Übersetzerbau, Section Introduction of Ch. 5 and 6

4.1 Attribute grammars

Attribute grammar (AG): specifies **dependent computations in abstract program trees;**
declarative: explicitly specified dependences only; a suitable order of execution is computed

Computations solve the tasks of semantic analysis (and transformation)

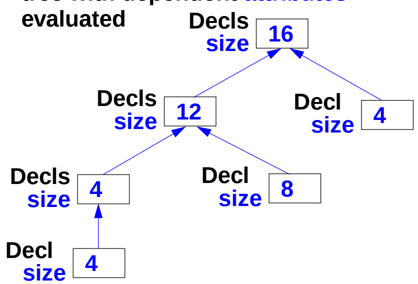
Generator produces **a plan for tree walks**
that execute calls of the computations,
such that the specified dependences are obeyed,
computed values are propagated through the tree

Result: attribute evaluator; applicable for any tree specified by the AG

Example: AG specifies size of declarations

```
RULE: Decls ::= Decls Decl COMPUTE
    Decls[1].size =
        Add (Decls[2].size, Decl.size);
END;
RULE: Decls ::= Decl COMPUTE
    Decls.size = Decl.size;
END;
RULE: Decl ::= Type Name COMPUTE
    Decl.size = Type.size;
END;
```

tree with dependent attributes evaluated



Lecture Programming Languages and Compilers WS 2013/14 / Slide 402

Objectives:

Get an informal idea of attribute grammars

In the lecture:

Explain computations in tree contexts using the example

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

Questions:

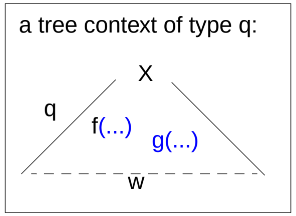
Why is it useful NOT to specify an evaluation order explicitly?

Basic concepts of attribute grammars (1)

An AG specifies **computations in trees** expressed by **computations associated to productions** of the abstract syntax

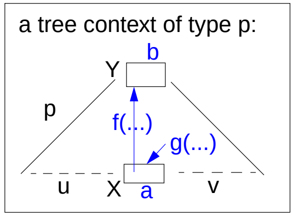
```
RULE q: X ::= w COMPUTE
   f(...); g(...);
END;
```

computations f(...) and g(...) are executed in every tree context of type q



An AG specifies **dependences between computations**: expressed by **attributes associated to grammar symbols**

```
RULE p: Y ::= u X v COMPUTE
   Y.b = f(X.a);
   X.a = g(...);
END;
```



Attributes represent: **properties of symbols** and
pre- and post-conditions of computations:
post-condition = f (pre-condition)
f(X.a) uses the result of g(...); hence
X.a = g(...) is specified to be executed before f(X.a)

Lecture Programming Languages and Compilers WS 2013/14 / Slide 403

Objectives:

Get a basic understanding of AGs

In the lecture:

Explain

- the AG notation,
- dependent computations

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

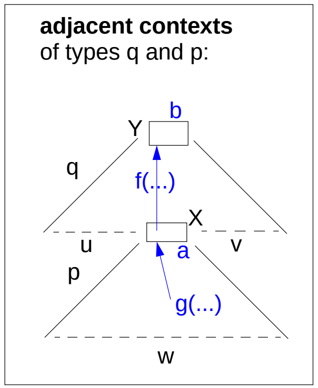
Assignments:

- Read and modify examples in Lido notation to introduce AGs

Basic concepts of attribute grammars (2)

dependent computations in adjacent contexts:

```
RULE q: Y ::= u X v COMPUTE
   Y.b = f(X.a);
END;
RULE p: X ::= w COMPUTE
   X.a = g(...);
END;
```



attributes may specify
dependences without propagating any value;
specifies the order of effects of computations:

```
X.GotType = ResetTypeOf(...);
Y.Type = GetTypeOf(...) <- X.GotType;
```

`ResetTypeOf` will be called before `GetTypeOf`

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Objectives:

Get a basic understanding of AGs

In the lecture:

Explain

- dependent computations in adjacent contexts in trees

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

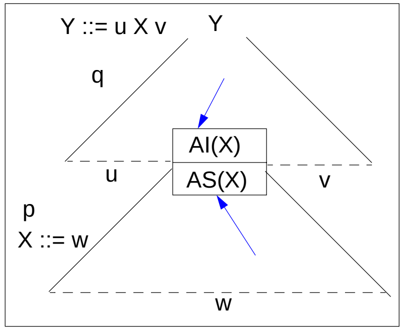
Assignments:

- Read and modify examples in Lido notation to introduce AGs

Definition of attribute grammars

An **attribute grammar** AG = (G, A, C) is defined by

- a **context-free grammar G** (abstract syntax)
- for each **symbol X** of G a set of **attributes A(X)**, written X.a if a ∈ A(X)
- for each **production (rule) p** of G a set of **computations** of one of the forms
  X.a = f (... Y.b ...)   or   g (... Y.b ...)
  where X and Y occur in p



Consistency and completeness of an AG:

Each A(X) is partitioned into two disjoint subsets: AI(X) and AS(X)

AI(X): **inherited attributes** are computed in rules p where X is on the **right**-hand side of p

AS(X): **synthesized attributes** are computed in rules p where X is on the **left**-hand side of p

Each rule p: Y::= ... X... has exactly one computation
for each attribute of AS(Y), for the symbol on the left-hand side of p, and
for each attribute of AI(X), for each symbol occurrence on the right-hand side of p

Lecture Programming Languages and Compilers WS 2013/14 / Slide 405

Objectives:

Formal view on AGs

In the lecture:

The completeness and consistency rules are explained using the example of PLaC-4.6

AG Example: Compute expression values

The AG specifies: The value of each expression is computed and printed at the root:

```
ATTR value: int;

RULE: Root ::=  Expr  COMPUTE
  printf ("value is %d\n",
          Expr.value);
END;

TERM Number: int;

RULE: Expr ::= Number COMPUTE
  Expr.value = Number;
END;

RULE: Expr ::= Expr Opr Expr
COMPUTE
  Expr[1].value = Opr.value;
  Opr.left  = Expr[2].value;
  Opr.right = Expr[3].value;
END;
```

```
SYMBOL Opr: left, right: int;

RULE: Opr ::=  '+'  COMPUTE
  Opr.value  =
     ADD (Opr.left, Opr.right);
END;

RULE: Opr ::=  '*'  COMPUTE
  Opr.value =
     MUL (Opr.left, Opr.right);
END;
```

A (Expr) = AS(Expr) = {value}

AS(Opr) = {value}
AI(Opr) = {left, right}

A(Opr) = {value, left, right}

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Objectives:

Exercise formal definition

In the lecture:

- Show synthesized, inherited attributes.
- Check consistency and completeness.

Questions:

- Add a computation such that a pair of sets AI(X), AS(X) is no longer disjoint.
- Add a computation such that the AG is inconsistent.
- Which computations can be omitted whithout making the AG incomplete?
- What would the effect be if the order of the three computations on the bottom left of the slide was altered?

AG Binary numbers

Attributes:	`L.v, B.v`	value
	`L.lg`	number of digits in the sequence L
	`L.s, B.s`	scaling of B or the least significant digit of L

```
RULE p1:   D ::= L '.' L   COMPUTE
   D.v = ADD (L[1].v, L[2].v);
   L[1].s = 0;
   L[2].s = NEG (L[2].lg);
END;
RULE p2:   L ::= L B       COMPUTE
   L[1].v = ADD (L[2].v, B.v);
   B.s = L[1].s;
   L[2].s = ADD (L[1].s, 1);
   L[1].lg = ADD (L[2].lg, 1);
END;
RULE p3:   L ::= B         COMPUTE
   L.v = B.v;
   B.s = L.s;
   L.lg = 1;
END;
RULE p4:   B ::= '0'       COMPUTE
   B.v = 0;
END;
RULE p5:   B ::= '1'       COMPUTE
   B.v = Power2 (B.s);
END;
```

scaled binary value:

`B.v = 1 * 2`$^{B.s}$

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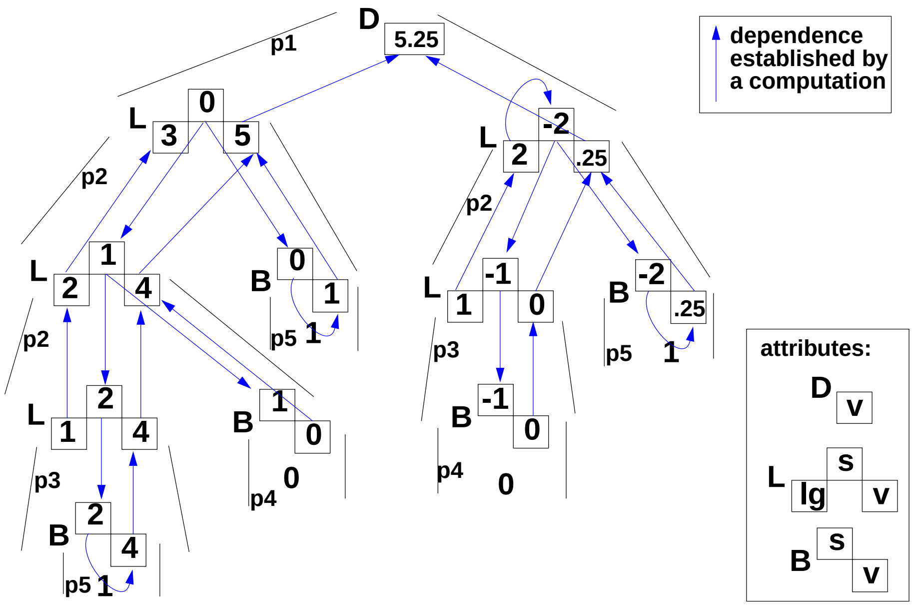
Objectives:

A complete example for an AG

In the lecture:

- Explain the task.
- Explain the role of the attributes.
- Explain the computations in tree contexts.
- Show a tree with attributes and dependencies (PLaC-4.8)

An attributed tree for AG Binary numbers



Lecture Programming Languages and Compilers WS 2013/14 / Slide 408

Objectives:

An attributed tree

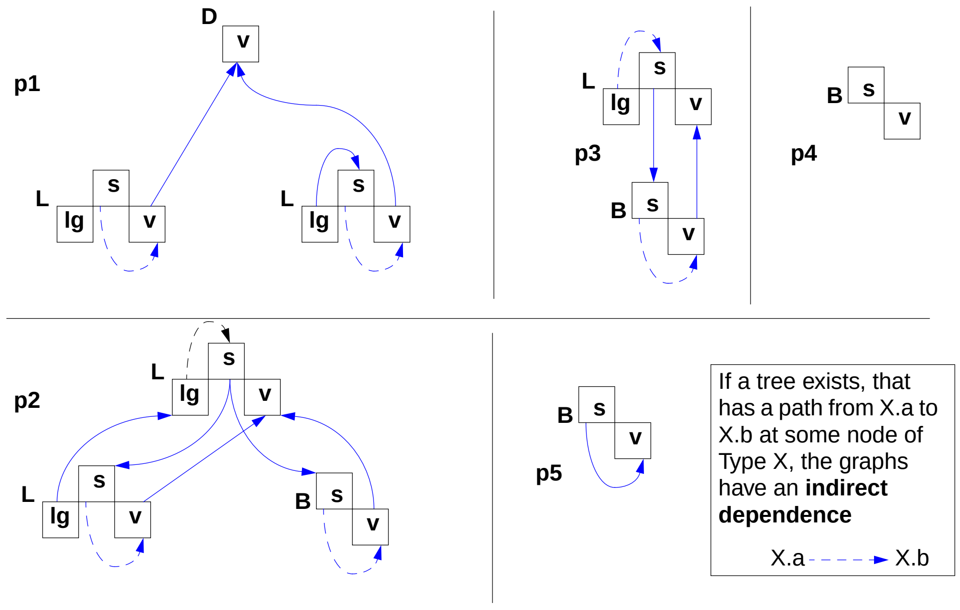
In the lecture:

- Show a tree with attributes.
- Show tree contexts specified by grammar rules.
- Relate the dependences to computations.
- Evaluate the attributes.

Questions:

- Some attributes do not have an incoming arc. Why?
- Show that the attribues of each L node can be evaluated in the order lg, s, v.

Dependence graphs for AG Binary numbers



If a tree exists, that has a path from X.a to X.b at some node of Type X, the graphs have an **indirect dependence**

X.a - - - -► X.b

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Objectives:

Represent dependences

In the lecture:

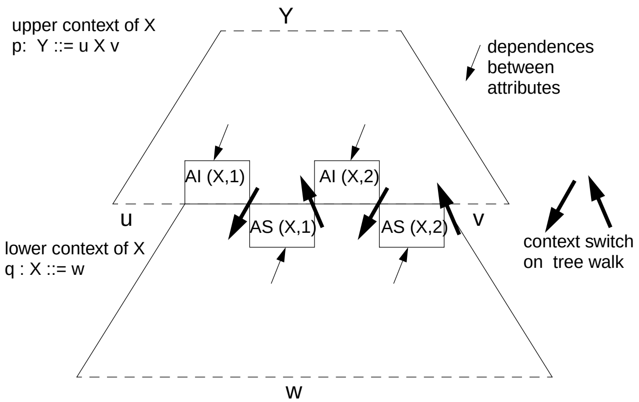
- graph representation of dependences that are specified by computations,
- compose the graphs to yield a tree with dependences,
- explain indirect dependences
- Use the graphs as an example for partitions (PLaC-4.9)
- Use the graphs as an example for LAG(k) algorithm (see a later slide)

Attribute partitions

The sets AI(X) and AS(X) are **partitioned** each such that

AI (X, i) is computed **before the i-th visit** of X

AS (X, i) is computed **during the i-th visit** of X



Necessary precondition for the existence of such a partition:
No node in any tree has **direct or indirect dependences that contradict the evaluation order** of the sequence of sets:AI (X, 1), AS (X, 1), ..., AI (X, k), AS (X, k)

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Objectives:

Understand the concept of attribute partitions

In the lecture:

Explain the concepts

- context switch,
- attribute partitions: sequence of disjoint sets which alternate between synthesized and inherited

Suggested reading:

Kastens / Übersetzerbau, Section 5.2

Assignments:

Construct AGs that are as simple as possible and each exhibits one of the following properties:

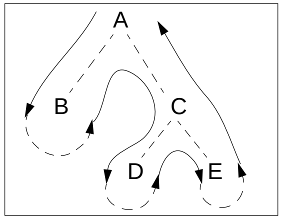
- There are some trees that have a dependence cycle, other trees don't.
- The cycles extend over more than one context.
- There is an X that has a partition with k=2 but not with k=1.
- There is no partition, although no tree exists that has a cycle. (caution: difficult puzzle!)

(Exercise 22)

Construction of attribute evaluators

For a given attribute grammar an attribute evaluator is constructed:

- It is **applicable to any tree** that obeys the abstract syntax specified in the rules of the AG.
- It performs a **tree walk** and **executes computations** in visited contexts.
- The execution order obeys the **attribute dependences**.



Pass-oriented strategies for the tree walk: **AG class:**

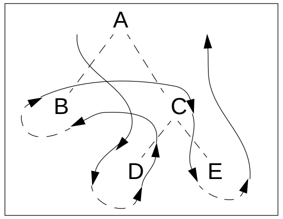
k times **depth-first left-to-right**	**LAG (k)**
k times depth-first right-to-left	RAG (k)
alternatingly left-to-right / right-to left	**AAG (k)**
once **bottom-up (synth. attributes only)**	**SAG**

AG is checked if attribute dependences
fit to desired pass-oriented strategy; see LAG(k) check.

non-pass-oriented strategies:

visit-sequences: **OAG**
an individual plan for each rule of the abstract syntax

A generator fits the plans to the dependences of the AG.



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Objectives:

Tree walk strategies

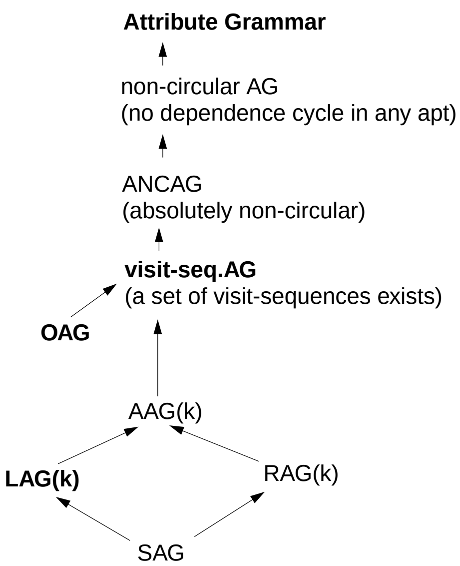
In the lecture:

- Show the relation between tree walk strategies and attribute dependences.

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

Hierarchy of AG classes



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Objectives:

Understand the AG hierarchy

In the lecture:

It is explained

- A grammar class is more powerful if it covers AGs with more complex dependencies.
- The relationship of AG classes in the hierarchy.

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

Visit-sequences

A **visit-sequence** (dt. Besuchssequenz) vs_p **for each production** of the tree grammar:

$p: X_o ::= X_1 \ldots X_i \ldots X_n$

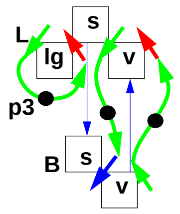
A visit-sequence is a **sequence of operations**:

↓ i, j	j-th **visit of the i-th subtree**
↑ j	j-th **return to the ancestor** node
$eval_c$	execution of a **computation** c associated to p

Example out of the AG for binary numbers:

vs_{p3}: L ::= B

L.lg=1; ↑1; B.s=L.s; ↓B,1; L.v=B.v; ↑2



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Objectives:

Understand the concept of visit-sequences

In the lecture:

Using the example it is explained:

- operations,
- context switch,
- sequence with respect to a context

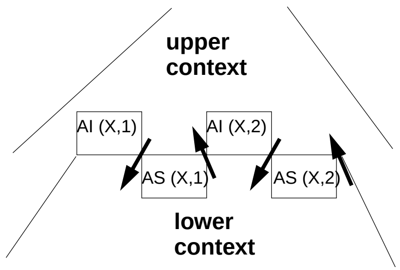
Suggested reading:

Kastens / Übersetzerbau, Section 5.2.2

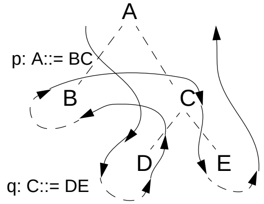
Interleaving of visit-sequences

Visit-sequences for adjacent contexts are executed interleaved.

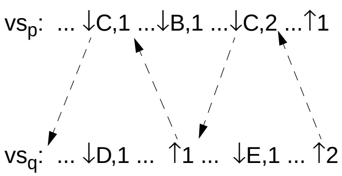
The **attribute partition** of the common nonterminal specifies the **interface** between the upper and lower visit-sequence:



Example in the tree:



interleaved visit-sequences:



Implementation:one **procedure for each section of a visit-sequence upto** ↑
a **call** with a switch over applicable productions for ↓

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Objectives:

Understand interleaved visit-sequences

In the lecture:

Explain

- interleaving of visit-sequences for adjacent contexts,
- partitions are "interfaces" for context switches,
- implementation using procedures and calls

Suggested reading:

Kastens / Übersetzerbau, Section 5.2.2

Assignments:

- Construct a set of visit-sequences for a small tree grammar, such that the tree walk solves a certain task.
- Find the description of the design pattern "Visitor" and relate it to visit-sequences.

Questions:

- Describe visit-sequences which let trees being traversed twice depth-first left-to-right.

Visit-sequences for the AG Binary numbers

vs_{p1}: D ::= L '.' L

↓L[1],1; L[1].s=0; ↓L[1],2; ↓L[2],1; L[2].s=NEG(L[2].lg);

↓L[2],2; D.v=ADD(L[1].v, L[2].v); ↑1

vs_{p2}: L ::= L B

↓L[2],1; L[1].lg=ADD(L[2].lg,1); ↑1

L[2].s=ADD(L[1].s,1); ↓L[2],2; B.s=L[1].s; ↓B,1; L[1].v=ADD(L[2].v, B.v); ↑2

vs_{p3}: L ::= B

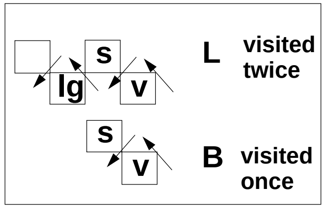
L.lg=1; ↑1; B.s=L.s; ↓B,1; L.v=B.v; ↑2

vs_{p4}: B ::= '0'

B.v=0; ↑1

vs_{p5}: B ::= '1'

B.v=Power2(B.s); ↑1



Implementation:

Procedure vs<i><p> for each section of a vs_p to a ↑i

a call with a switch over alternative rules for ↓X,i

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Objectives:

Example for visit-sequences used in PLaC-4.13

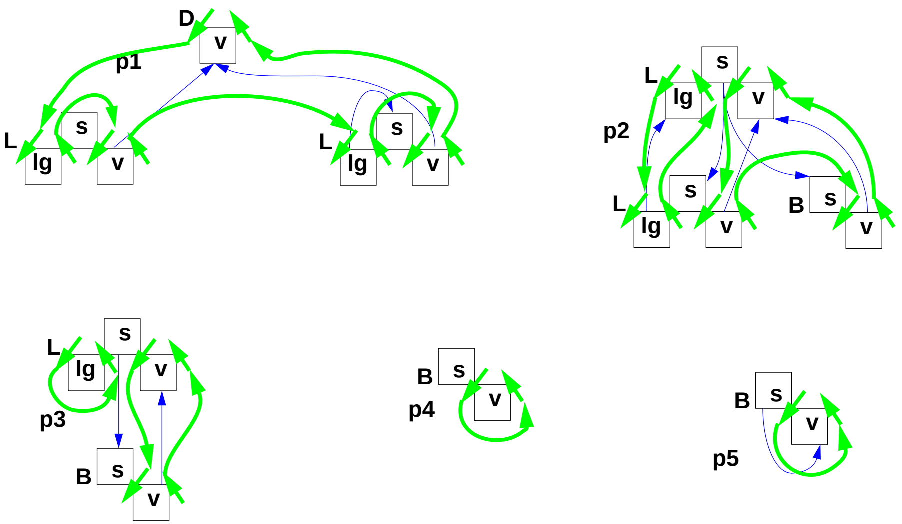
In the lecture:

- Show interfaces and interleaving,
- show tree walk (PLaC-4.15),
- show sections for implementation.

Questions:

- Check that adjacent visit-sequences interleave correctly.
- Check that all dependencies between computations are obeyed.
- Write procedures that implement these visit-sequences.

Visit-Sequences for AG Binary numbers (tree patterns)



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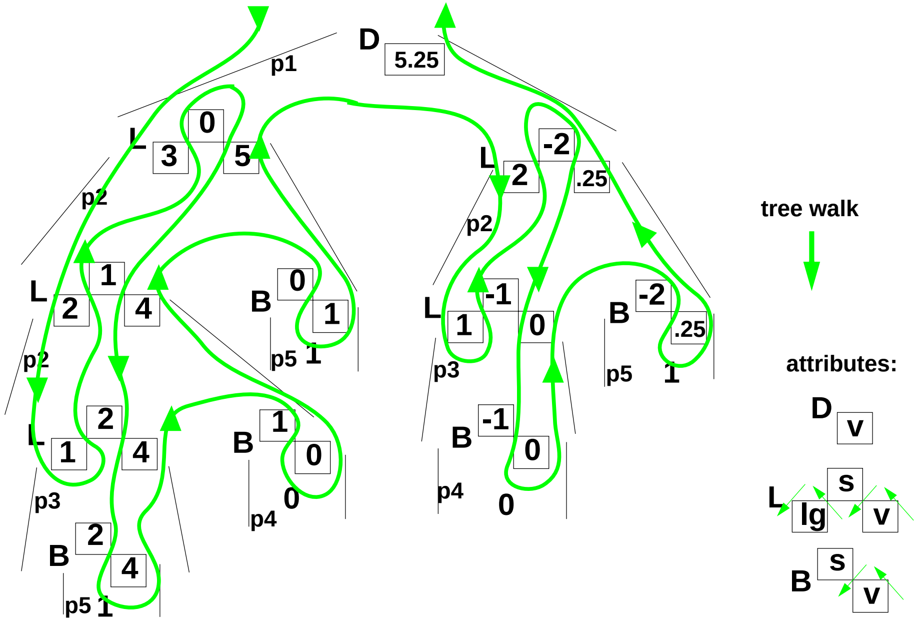
Objectives:

Example for visit-sequences used in PLaC-4.13

In the lecture:

- Create a tree walk by pasting instances of visit-sequnces together

Tree walk for AG Binary numbers



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Objectives:

See a concrete tree walk

In the lecture:

Show that the visit-sequences of PLaC-4.15 produce this tree walk for the tree of PLaC-4.8.

LAG (k) condition

An AG is a LAG(k), if:

For each symbol X there is an **attribute partition** A (X,1), ..., A (X, k),
such that the attributes in **A (X, i) can be computed in the i-th depth-first left-to-right pass**.

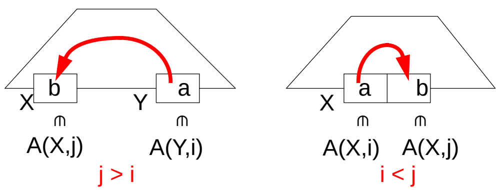
Crucial dependences:

In every dependence graph every dependence

- **Y.a -> X.b** where X and Y occur on the **right-hand side** and **Y is right of X** implies that **Y.a belongs to an earlier pass than X.b**, and
- **X.a -> X.b** where X occurs on the **right-hand side** implies that **X.a belongs to an earlier pass than X.b**

Necessary and sufficient condition over dependence graphs - expressed graphically:

A dependency **from right to left**



A dependence **at one symbol** on the right-hand side

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Objectives:

Understand the LAG condition

In the lecture:

- Explain the LAG(k) condition,
- motivate it by depth-first left-to-right tree walks.

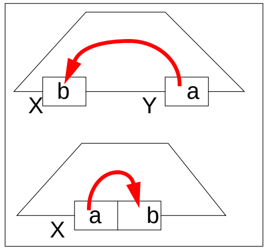
Suggested reading:

Kastens / Übersetzerbau, Section 5.2.3

LAG (k) algorithm

Algorithm checks whether there is a **k>=1** such that an **AG is LAG(k)**.

Method:
compute iteratively **A(1)**, ..., **A(k)**;
in each iteration try to allocate all remaining attributes to the current pass, i.e. **A(i)**;
remove those which can not be evaluated in that pass



Algorithm:

Set **i=1** and **Cand=** all attributes

repeat
set **A(i) = Cand**; set **Cand** to empty;

while still attributes can be removed from **A(i)** do
remove an attribute X.b from A(i) and add it to **Cand** if
- there is a **crucial dependence**
Y.a -> X.b s.t.
X and **Y** are on the right-hand side, **Y** to the right of **X** and **Y.a** in **A(i)** or
X.a -> X.b s.t. **X** is on the right-hand side and **X.a** is in **A(i)**
- **X.b** depends on an attribute that is not yet in any **A(i)**

if **Cand** is empty: exit: the AG **is LAG(k)** and all attributes are assigned to their passes
if **A(i)** is empty: exit: the AG **is not LAG(k) for any k**
else: set i = i + 1

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Objectives:
Understand the LAG(k) check

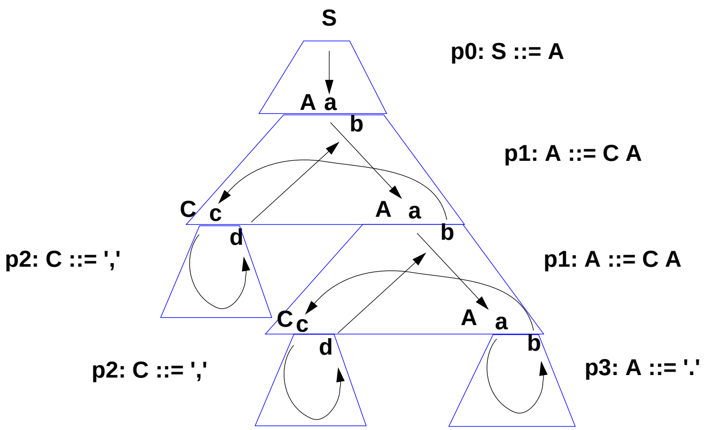
In the lecture:
- explain the algorithm using the example of PLaC-4.10.

Suggested reading:
Kastens / Übersetzerbau, Section 5.2.3

Assignments:
- Check LAG(k) condition for AGs (Exercise 20)

Questions:
- At the end of each iteration of the i-loop one of three conditions hold. Explain them.

AG not LAG(k) for any k



A.a can be allocated to the first left-to-right pass.
C.c, C.d, A.b can not be allocated to any pass.

The AG is RAG(1), AAG(2) and
can be evaluated by visit-sequences.

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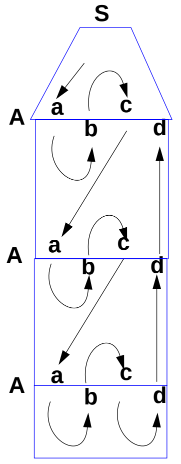
Objectives:
Understand a non-LAG pattern

In the lecture:
- Explain the tree,
- derive the AG,
- try the LAG(k) algorithm.

AG not evaluable in passes



p0: S ::= A

p1: A ::= ',' A

p1: A ::= ',' A

p2: A ::= '.'

No attribute can be allocated to any pass for any strategy.

The AG can be evaluated by visit-sequences.

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Objectives:

Understand a non-pass pattern

In the lecture:

- Explain the tree,
- derive the AG,
- try the LAG(k) algorithm.

Generators for attribute grammars

LIGA	University of Paderborn	OAG
FNC-2	INRIA	ANCAG (superset of OAG)
CoCo	Universität Linz	LAG(k)

Properties of the generator LIGA

- integrated **in the Eli system**, cooperates with other Eli tools
- **high level specification language** Lido
- modular and **reusable AG components**
- object-oriented constructs usable for **abstraction of computational patterns**
- computations are **calls of functions** implemented outside the AG
- **side-effect computations** can be controlled by dependencies
- notations for **remote attribute access**
- **visit-sequence** controlled attribute evaluators, implemented in C
- **attribute storage optimization**

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Objectives:

See what generators can do

In the lecture:

- Explain the generators
- Explain properties of LIGA

Suggested reading:

Kastens / Übersetzerbau, Section 5.4

Explicit left-to-right depth-first propagation

```
ATTR pre, post: int;
RULE: Root ::= Block COMPUTE
  Block.pre = 0;
END;
RULE: Block ::= '{' Constructs '}' COMPUTE
  Constructs.pre = Block.pre;
  Block.post = Constructs.post;
END;
RULE: Constructs ::= Constructs Construct COMPUTE
  Constructs[2].pre = Constructs[1].pre;
  Construct.pre = Constructs[2].post;
  Constructs[1].post = Construct.post;
END;
RULE: Constructs ::= COMPUTE
  Constructs.post = Constructs.pre;
END;
RULE: Construct ::= Definition COMPUTE
  Definition.pre = Construct.pre;
  Construct.post = Definition.post;
END;
RULE: Construct ::= Statement COMPUTE
  Statement.pre = Construct.pre;
  Construct.post = Statement.post;
END;
RULE:Definition ::= 'define' Ident ';' COMPUTE
  Definition.printed =
     printf ("Def %d defines %s in line %d\n",
             Definition.pre, StringTable (Ident), LINE);
  Definition.post =
     ADD (Definition.pre, 1) <- Definition.printed;
END;
RULE: Statement ::= 'use' Ident ';' COMPUTE
  Statement.post = Statement.pre;
END;
RULE: Statement ::= Block COMPUTE
  Block.pre = Statement.pre;
  Statement.post = Block.post;
END;
```

Definitions are enumerated and printed from left to right.

The next **Definition** number is propagated by a pair of attributes at each node:

pre (inherited)
post (synthesized)

The value is initialized in the **Root** context and

incremented in the **Definition** context.

The computations for propagation are systematic and redundant.

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Objectives:

Understand left-to-right propagation

In the lecture:

Explain

- systematic use of attribute pairs for propagation,
- strict dependences of computations on the "propagation chain".

Questions:

How would the output look like if we had omitted the state attributes and their dependencies?

Left-to-right depth-first propagation using a CHAIN

```
CHAIN count: int;

RULE: Root ::= Block COMPUTE
   CHAINSTART Block.count = 0;
END;

RULE: Definition ::= 'define' Ident ';'
COMPUTE
   Definition.print =
      printf ("Def %d defines %s in line %d\n",
              Definition.count, /* incoming */
              StringTable (Ident), LINE);

   Definition.count = /* outgoing */
      ADD (Definition.count, 1)
      <- Definition.print;
END;
```

A **CHAIN** specifies a **left-to-right depth-first** dependency through a subtree.

One CHAIN name; attribute pairs are generated where needed.

CHAINSTART initializes the CHAIN in the root context of the CHAIN.

Computations on the CHAIN are **strictly bound** by dependences.

Trivial computations of the form X.pre = Y.pre in CHAIN order can be **omitted**. They are generated where needed.

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Objectives:

Understand LIDO's CHAIN constructs

In the lecture:

- Explain the CHAIN constructs.
- Compare the example with PLaC-4.19.

Dependency pattern INCLUDING

```
ATTR depth: int;
RULE: Root ::= Block COMPUTE
  Block.depth = 0;
END;
RULE: Statement ::= Block COMPUTE
  Block.depth =
     ADD (INCLUDING Block.depth, 1);
END;
RULE: Definition ::= 'define' Ident  COMPUTE
  printf ("%s defined on depth %d\n",
           StringTable (Ident),
           INCLUDING Block.depth);
END;
```

INCLUDING Block.depth
accesses the **depth** attribute of the next upper node of type **Block.**

The nesting depths of **Blocks** are computed.

An **attribute** at the root of a subtree is **accessed from within the subtree**.

Propagation from computation to the uses are generated as needed.

No explicit computations or attributes are needed for the remaining rules and symbols.

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Objectives:
Understand the LIDO construct INCLUDING

In the lecture:
Explain the use of the INCLUDING construct.

Dependency pattern CONSTITUENTS

```
RULE: Root ::= Block COMPUTE
   Root.DefDone =
      CONSTITUENTS Definition.DefDone;
END;

RULE: Definition ::= 'define' Ident ';'
COMPUTE
   Definition.DefDone =
      printf ("%s defined in line %d\n",
              StringTable (Ident), LINE);
END;

RULE: Statement ::= 'use' Ident ';' COMPUTE
   printf ("%s used in line %d\n",
            StringTable (Ident), LINE)
   <- INCLUDING Root.DefDone;

END;
```

CONSTITUENTS Definition.DefDone accesses the **DefDone** attributes of all **Definition** nodes in the subtree below this context

A **CONSTITUENTS** computation **accesses attributes from the subtree below** its context.

Propagation from computation to the **CONSTITUENTS** construct is generated where needed.

The shown combination with **INCLUDING** is a common dependency pattern.

All **printf** calls in **Definition** contexts are done before any in a **Statement** context.

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Objectives:
Understand the LIDO construct CONSTITUENTS

In the lecture:
Explain the use of the CONSTITUENTS construct.

5. Binding of Names
5.1 Fundamental notions

Program entity: An **identifiable** entity that has **individual properties**, is used potentially at **several places in the program**. Depending on its **kind** it may have one or more runtime instances; e. g. type, function, variable, label, module, package.

Identifiers: a class of tokens that are used to **identify program entities; e. g.** `minint`

Name: a **composite construct** used to **identify a program entity**, usually contains an identifier; e. g. `Thread.sleep`

Static binding: A binding is established **between a name and a program entity**. It is **valid** in a certain area of the **program text**, the **scope of the binding.** There the name identifies the program entity. Outside of its scope the name is unbound or bound to a different entity. Scopes are expressed in terms of program constructs like blocks, modules, classes, packets

Dynamic binding: Bindings are established in the **run-time** environment; e. g. in Lisp.

A **binding may be established**

- **explicitly by a definition**; it usually **defines properties** of the program entity; we then destinguish **defining and applied occurrences** of a name; e. g. in C: `float x = 3.1; y = 3*x;` or in JavaScript: `var x;`
- **implicitly by using the name**; properties of the program entity may be defined by the context; e. g. bindings of global and local variables in PHP

Objectives:

Repeat and understand notions

In the lecture:

Explanations and examples for

- program entities in contrast to program constructs,
- no, one or several run-time instances,
- bindings established explicitly and imlicitly

Suggested reading:

Kastens / Übersetzerbau, Section 6.2, 6.2.2

5.2 Scope rules

Scope rules: a set of rules that specify for a given language how bindings are established and where they hold.

2 variants of fundamental **hiding rules** for languages with nested structures.
Both are based on **definitions that explicitly introduce bindings**:

Algol rule:
The definition of an identifier *b* is valid in the **whole smallest enclosing range**; but **not in inner ranges** that have a **definition of *b***, too.

e. g. in Algol 60, Pascal, Java

C rule:
The definition of an identifier b is valid in the **smallest enclosing range from the position of the definition** to the end; but **not in inner ranges** that have another **definition of b** from the position of that definition to the end.

e. g. in C, C++, Java

Algol rule (a a) | **C rule** (a a)

```
{
   int a;
   {
      int b = a;
      float a;
      a = b+1;
   }
   a = 5;
}
```


Objectives:

Repeat fundamental hiding rules

In the lecture:

Explanations and examples for

- hiding rules (see "Grundlagen der Programmiersprachen"),
- occurrences of the Algol rule in Pascal (general), C (labels), Java (instance variables).

Suggested reading:

Kastens / Übersetzerbau, Section 6.2, 6.2.2

Defining occurrence before applied occurrences

The **C rule** enforces the defining occurrence of a binding precedes all its applied occurrences.

In Pascal, Modula, Ada the **Algol rule** holds. An **additional rule** requires that the defining occurrence of a binding precedes all its applied occurrences.

Consequences:

- specific constructs for **forward references of functions** which may call each other recursively:
  `forward` function declaration in Pascal;
  function declaration in C before the function definition,
  exemption form the def-before-use-rule in Modula
- specific constructs for **types** which may contain **references** to each other **recursively**:
  forward type references allowed for pointer types in Pascal, C, Modula
- specific rules for labels to allow **forward jumps**:
  label declaration in Pascal before the label definition,
  Algol rule for labels in C
- (Standard) **Pascal** requires **declaration parts** to be structured as a sequence of declarations for constants, types, variables and functions, such that the former may be used in the latter. **Grouping by coherence criteria** is not possible.

Algol rule is **simpler, more flexible** and allows for **individual ordering** of definitions according to design criteria.

Objectives:

Understand consequences

In the lecture:

Explanations and examples for the mentioned consequences, constructs and rules.

Multiple definitions

Usually a **definition** of an identifier is required to be **unique** in each range. That rule guarantees that at most one binding holds for a given (plain) identifier in a given range.

Deviations from that rule:

- Definitions for the same binding are allowed to be repeated, e. g. in C
  `external int maxElement`;
- Definitions for the same binding are allowed to accumulate properties of the program entity, e. g. AG specification language LIDO: association of attributes to symbols:
  ```
  SYMBOL AppIdent: key: DefTableKey;
  ...
  SYMBOL AppIdent: type: DefTableKey;
  ```
- **Separate name spaces** for bindings of different kinds of program entities. Occurrences of identifiers are syntactically distinguished and associated to a specific name space, e. g. in Java bindings of packets and types are in different name spaces:
  `import Stack.Stack;`
  in C labels, type tags and other bindings have their own name space each.
- **Overloading** of identifiers: **different program entities are bound to one identifier** with overlapping scopes. They are **distinguished by static semantic information** in the context, e. g. overloaded functions distinguished by the signature of the call (number and types of actual parameters).

Objectives:

Understand variants of multiple definitions

In the lecture:

Explanations and examples for

- the variants,
- their usefulness

Explicit Import and Export

Bindings may be **explicitly imported to or exported from a range** by specific language constructs. Such features have been introduced in languages like Modula-2 in order to support **modular decomposition and separate compilation**.

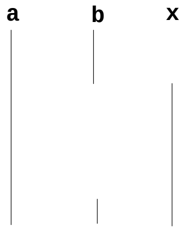
Modula-2 defines two different import/export features

1. **Separately compiled modules**:

```
DEFINITION MODULE Scanner;          interface of a separately compiled module
   FROM Input IMPORT Read, EOL;                          imported bindings
   EXPORT QUALIFIED Symbol, GetSym;                      exported bindings
   TYPE Symbol = ...;                       definitions of exported bindings
   PROCEDURE GetSym;
END Scanner;
IMPLEMENTATION MODULE Scanner BEGIN ... END Scanner;
```

2. **Local modules, embedded in the block structure** establish scope boundaries:

```
VAR a, b: INTEGER;
...
MODULE m;
   IMPORT a;
   EXPORT x;
   VAR x: REAL;
BEGIN ... END m;
...
```



Lecture Programming Languages and Compilers WS 2011/12 / Slide 505

Objectives:

Understand explicit extension of scopes

In the lecture:

Explanations and examples for

- explicit import / export in contrast to implicit hiding,
- scopes related to interfaces,
- import of packets in Java.

Bindings as properties of entities

Program entities may have a property that is a set of bindings, e. g. the entities exported by a module interface or the fields of a struct type in C:

```
typedef struct {int x, y;} Coord;

Coord anchor[5];
anchor[0].x = 42;
```

The type **Coord** has the bindings of its fields as its property; **anchor[0]** has the type **Coord**; **x** is bound in its set of bindings.

Language constructs like the **with**-statement of Pascal insert such sets of bindings into the bindings of nested blocks:

```
type Coord = record x, y: integer; end;
var  anchor: array [0..4] Coord;
     a, x: real;
begin ...
   with anchor[0] do
      begin ...
         x := 42;
      end;
   ...
end;
```

Bindings of the type **Coord** are inserted into the textually nested scopes; hence the field **x** hides the variable **x**.

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Objectives:

Understand bindings as properties

In the lecture:

Explanations and examples for

- sets of bindings,
- used in qualified names,
- used in with-statements,
- name analysis depends on type analysis.

Inheritance with respect to binding

Inheritance is a **relation between object oriented classes**. It defines the basis for **dynamic binding of method calls**. However, **static binding rules** determine the **candidates for dynamic binding** of method calls.

A class has a **set of bindings as its property**.

It consists of the bindings **defined in the class** and those **inherited** from classes and interfaces.

An **inherited binding may be hidden** by a local definition.

That set of bindings is used for identifying qualified names (cf. `struct` types):

```
D d = new D; d.f();
```

A class may be **embedded in a context** that provides bindings. An unqualified name as in `f()` is bound in the **class's local and inherited** sets, and **then** in the **bindings of the textual context** (cf. `with`-statement).

```
class E
{  void f(){...}
   void h(){...}
   ...
}
```

```
class D
   extends E
{  void f(){...}
   void g(){...}
   ...
}
```

```
interface I
{  public void k();
}
```

```
class A
{ void f(){...}
   class C
      extends D implements I
   { void tr(){ f(); h();}
   }
}
```


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Objectives:

Understand inheritance relation

In the lecture:

The example is used to explain

- inheritance hierarchy,
- hiding via inheritance,
- binding of qualified and unqualified names,
- nested classes,
- relation to dynamic method calls.

5.3 An environment module for name analysis

The compiler represents a **program entity by a key**. It references a description of the entity's properties.

Name analysis task: Associate the **key of a program entity to each occurrence of an identifier** according to **scope rules** of the language (consistent renaming).
the pair (identifier, key) represents a binding.

Bindings that have a **common scope** are composed to **sets**.

An **environment** is a **linear sequence of sets of bindings** e_1, e_2, e_3, ... that are connected by a **hiding relation**: a binding (a, k) in e_i hides a binding (a,h) in e_j if $i < j$.

Scope rules can be modeled using the concept of **environments**.

The **name analysis task** can be **implemented** using a **module** that implements **environments** and operations on them.

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Objectives:

Understand the name analysis task

In the lecture:

Explanations and examples for

- environments,
- use of environments to model scope rules.

Environment module

Implements the abstract data type **Environment**:
hierarchically nested sets of **Binding**s **(identifier, environment, key)**
(The binding pair (i,k) is extended by the environment to which the binding belongs.)

Functions:

NewEnv ()	creates a new Environment e, to be used as root of a hierarchy
NewScope (e_1)	creates a new Environment e_2 that is nested in e1. Each binding of e_1 is also a binding of e_2 if it is not hidden there.
BindIdn (e, id)	introduces a binding (id, e, k) if e has no binding for id; then k is a new key representing a new entity; in any case the result is the binding triple (id, e, k)
BindingInEnv (e, id)	yields a binding triple (id, e_1, k) of e or a surrounding environment of e; yields NoBinding if no such binding exists.
BindingInScope (e, id)	yields a binding triple (id, e, k) of e, if contained directly in e, NoBinding otherwise.

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Objectives:

Learn the interface of the Environment module

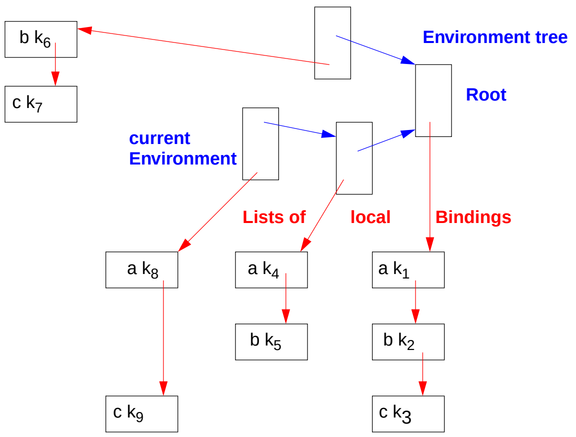
In the lecture:

- Explain the notion of Environment,
- explain the examples of scope rules,
- the module has further functions that allow to model inheritance, too.

Suggested reading:

Kastens / Übersetzerbau, Section 6.2.2

Data structure of the environment module (1)



k_i: key of the defined entity

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Objectives:

An search structure for definitions

In the lecture:

Explanations and examples for

- the environment tree,
- the binding lists.
- Each search has complexity O(n) in the number of definitions n.

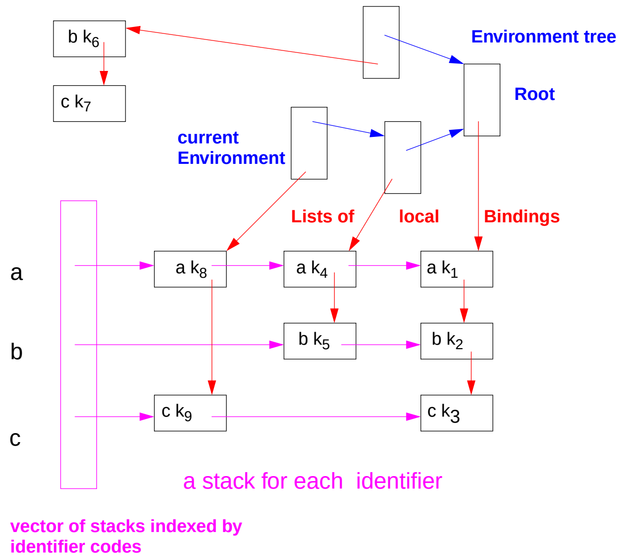
Suggested reading:

Kastens / Übersetzerbau, Section 6.2.2

Questions:

- How is a binding for a particular identifier found in this structure?
- How is determined that there is no valid binding for a particular identifier and a particular environment.

Data structure of the environment module (2)



k_i: key of the defined entity

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Objectives:

An efficient search structure

In the lecture:

Explanations and examples for

- the concept of identifier stacks,
- the effect of the operations,
- O(1) access instaed of linear search,
- how the current environment is changed using operations Enter and Leave, which insert a set of bindings into the stacks or remove it.

Suggested reading:

Kastens / Übersetzerbau, Section 6.2.2

Questions:

- In what sense is this data structure efficient?
- Describe a program for which a linear search in definition lists is more efficient than using this data structure.
- The efficiency advantage may be lost if the operations are executed in an unsuitable order. Explain!
- How can the current environment be changed without calling Enter and Leave explicitly?

Environment operations in tree contexts

Operations in tree contexts and the order they are called can **model scope rules**:

Root context:

```
Root.Env = NewEnv ();
```

Range context that may contain definitions:

```
Range.Env = NewScope (INCLUDING (Range.Env, Root.Env));
```

accesses the next enclosing Range or Root

defining occurrence of an identifier `IdDefScope`:

```
IdDefScope.Bind = BindIdn (INCLUDING Range.Env, IdDefScope.Symb);
```

applied occurrence of an identifier `IdUseEnv`:

```
IdUseEnv.Bind = BindingInEnv (INCLUDING Range.Env, IdUseEnv.Symb);
```

Preconditions for specific scope rules:

Algol rule: all `BindIdn()` of all surrounding ranges before any `BindingInEnv()`
C rule: `BindIdn()` and `BindingInEnv()` in textual order

The resulting **bindings are used for checks and transformations**, e. g.

- no applied occurrence without a valid defining occurrence,
- at most one definition for an identifier in a range,
- no applied occurrence before its defining occurrence (Pascal).

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Objectives:

Apply environment module in the program tree

In the lecture:

- Explain the operations in tree contexts.
- Show the effects of the order of calls.

Suggested reading:

Kastens / Übersetzerbau, Section 6.2.1

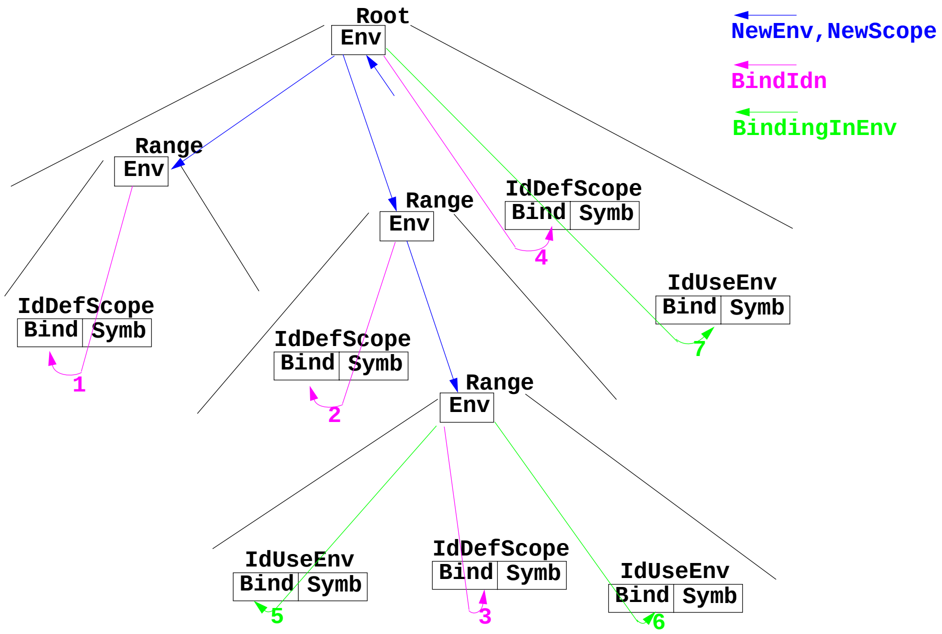
Assignments:

Use Eli module for a simple example.

Questions:

- How do you check the requirement "definition before application"?
- How do you introduce bindings for predefined entities?
- Assume a simple language where the whole program is the only range. There are no declarations, variables are implicitly declared by using their name. How do you use the operations of the environment module for that language?

Attribute computations for binding of names



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Objectives:

Understand dependences for name analysis

In the lecture:

- Identify the computations of the environment structure (blue), insertion of bindings in environments (magenta), lookup of a binding in an environment (green);
- order for Algol rules: (4 before 7) and (2, 3, 4 before 5, 6)
- order for C rules: 1, 2, 5, 3, 6, 4, 7

6. Type specification and type analysis

A **type** characterizes a set of (simple or structured) values and the applicable operations.

The language design constrains the way how values may interact.

Strongly typed language:
The implementation can guarantee that all type constraints can be checked

- **at compile time (static typing):** compiler finds type errors (developer), or
- **at run time (dynamic typing):** run time checks find type errors (tester, user).

static typing (plus run time checks): Java (strong); C, C++, Pascal, Ada (almost strong)
dynamic: script languages like Perl, PHP, JavaScript
no typing: Prolog, Lisp

Statically typed language:
Programmer declares type property - compiler checks (most languages)
Programmer uses typed entities - compiler infers their type properties (e.g. SML)

Compiler keeps track of the type of any

- **defined entity that has a value** (e. g. variable); stores type property in the definition module
- **program construct** elaborates to a value (e. g. expressions); stores type in an attribute

Lecture Programming Languages and Compilers WS 2011/12 / Slide 601

Objectives:

Fundamentals of typing constrains

In the lecture:

- Motivate type analysis tasks with typical properties of strongly typed languages;
- give examples

Suggested reading:

Kastens / Übersetzerbau, Section 6.1

Questions:

- Give examples for program entities that have a type property and for others which don't.
- Enumerate at least 5 properties of types in Java, C or Pascal.
- Give an example for a recursively defined type, and show its representation using keys.

Concepts for type analysis

Type: characterization of a subset of the values in the universe of operands available to the program. „a triple of int values“

Type denotation: a source-language construct used to denote a user-defined typ (language-defined types do not require type denotations).
`typedef struct {int year, month, day;} Date;`

sameType: a partition defining type denotations that might denote the same type.

Type identifier: a name used in a source-language program to specify a type.
`typedef struct {int year, month, day;} Date;`

Typed identifier: a name used in a source-language program to specify an entity (such as a variable) that can take any value of a given type.
`int count;`

Operator: an entity having a signature that relates operand types to a result type.
`iAdd: int x int -> int`

Indication: a set of operators with different signatures.
`{iAdd, fAdd, union, concat}`

acceptableAs: a partial order defining the types that can be used in a context where a specific type is expected. `short -> int -> long`

Lecture Programming Languages and Compilers WS 2011/12 / Slide 602

Objectives:

Understand fundamental concepts

In the lecture:

- concepts are language independent,
- give examples of different languages

Suggested reading:

Kastens / Übersetzerbau, Section 6.1

Questions:

- Give further examples for instances of these concepts

Taxonomy of type systems

[Luca Cardelli and Peter Wegner. On understanding types, data abstraction, and polymorphism. ACM Computing Surveys, 17(4):471–523, 1985.]

- **monomorphism**: Every entity has a unique type. Consequence: different operators for similar operations (e.g. for `int` and `float` addition)

- **polymorphism**: An operand may belong to several types.

-- **ad hoc polymorphism**:

--- **overloading**: a construct may different meanings depending on the context in which it appears (e.g. + with 4 different signatures in Algol 60)

--- **coercion**: implicit conversion of a value into a corresponding value of a different type, which the compiler can insert wherever it is appropriate (only 2 add operators)

-- **universal polymorphism**: operations work uniformly on a range of types that have a common structure

--- **inclusion polymorphism**: sub-typing as in object-oriented languages

--- **parametric polymorphism**: **polytypes** are type denotations with type parameters, e.g. `('a x 'a)`, `('a list x ('a -> 'b) -> 'b list)`
All types derivable from a polytype have the **same type abstraction**.
Type parameters are substituted by type **inference** (SML, Haskell) or by **generic instantiation** (C++, Java)

see GPS 5.9 - 5.10

Lecture Programming Languages and Compilers WS 2011/12 / Slide 603

Objectives:

Understand characteristics of type systems

In the lecture:

- different polymorphisms are explained using examples of different languages;
- consequences for type analysis are pointed out.

Suggested reading:

Kastens / Übersetzerbau, Section 6.1

Questions:

- Which characteristics are exhibited in Java and in C?

Monomorphism and ad hoc polymorphism

- **monomorphism (1)**
- **polymorphism**
  - **ad hoc polymorphism**
    - **overloading (2)**
    - **coercion (3)**
  - **universal polymorphism**
    - **inclusion polymorphism (4)**
    - **parametric polymorphism (5)**

monomorphism (1):
4 different names for addition:

```
addII: int   x int   -> int
addIF: int   x float -> float
addFI: float x int   -> float
addFF: float x float -> float
```

overloading (2):
1 name for addition **+**;
4 signatures are distinguished by actual operand and result types:

```
+: int   x int   -> int
+: int   x float -> float
+: float x int   -> float
+: float x float -> float
```

coercion (3):
`int` is acceptableAs **`float`**,
2 names for two signatures:

```
addII: int   x int   -> int
addFF: float x float -> float
```


Lecture Programming Languages and Compilers WS 2011/12 / Slide 603a

Objectives:
Examples illustrate monomorphism and ad hoc polymorphism

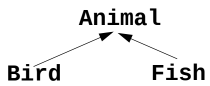
In the lecture:
- The examples are explained

Suggested reading:
Kastens / Übersetzerbau, Section 6.1

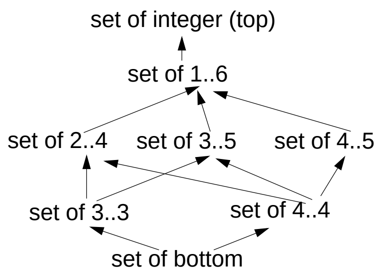
Examples for inclusion polymorphism (4)

Sub-typing:
S ist a **sub-type of** type T, S **<:** T, if each value of S is acceptable where a value of type T is expected.

Sub-type relation established by classes in **object-oriented languages**

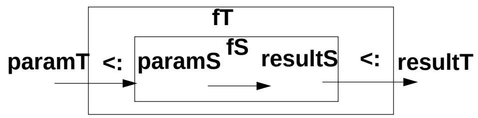


Lattice of set types in Pascal:



A **function** of type **fS** can be called where a function of type **fT** is expected, i.e. **fS <: fT,** if

fT = paramT -> resultT **paramT <: paramS**
fS = paramS -> resultS **resultS <: resultT**



Lecture Programming Languages and Compilers WS 2011/12 / Slide 603b

Objectives:
Understand inclusion polymorphism

In the lecture:
- The central rule,
- OO sub-typing,
- type safe overriding,
- contravariant parameter types

are explained.

Suggested reading:
Kastens / Übersetzerbau, Section 6.1

Compiler's definition module

Central data structure, **stores properties of program entities**
e. g. *type of a variable, element type of an array type*

A **program entity** is identified by the **key** of its entry in this data structure.

Operations:

NewKey ( )	yields a new key
ResetP (k, v)	sets the property P to have the value v for key k
SetP (k, v, d)	as ResetP; but the property is set to d if it has been set before
GetP (k, d)	yields the value of the Property P for the key k; yields the default value d, if P has not been set

Operations are **called in tree contexts**, dependences control accesses, e. g. SetP before GetP

Implementation of data structure: a property list for every key

Definition module is generated from specifications of the form

Property name :   property type;
`ElementNumber: int;`

Generated functions: **`ResetElementNumber`**, **`SetElementNumber`**, **`GetElementNumber`**

Lecture Programming Languages and Compilers WS 2011/12 / Slide 604

Objectives:

Properties of program entities

In the lecture:

- Explain the operations,
- explain the generator,
- give examples.

Assignments:

- Use the PDL tool of Eli to specify properties of SetLan entities.

Questions:

- Give examples where calls of the operations are specified as computations in tree contexts. Describe how they depend on each other.

Language defined entities

Language-defined types, operators, and indications are represented by **known keys** - definition table keys, created by initialization and made available as **named constants**.

Eli's specification language OIL can be used to specify language defined types, operators, and indications, e.g.:

```
OPER
   iAdd (intType,intType):intType;
   rAdd (floatType,floatType):floatType;

INDICATION
   PlusOp: iAdd, rAdd;

COERCION
   (intType):floatType;
```

It results in known keys for two types, two operators, and an indication. The following identifiers can be used to name those keys in tree computations:

```
intType, floatType, iAdd, rAdd, PlusOp

RULE: Operator ::= '+' COMPUTE Operator.Indic = PlusOp;END;
```

The coercion establishes the language-defined relation

```
intType acceptableAs floatType
```


Lecture Programming Languages and Compilers WS 2011/12 / Slide 605

Objectives:

Specification of overloaded operators and coercion

In the lecture:

Explain the signatures, indications, and coercions

Assignments:

- Use the OIL tool of Eli to specify SetLan operators

Language-defined and user-defined types

A **language-defined type** is represented by a keyword in a program. The compiler determines sets an attribute **Type.Type**:

```
RULE: Type ::= 'int' COMPUTE
   Type.Type = intType;
END;
```

The type analysis modules of Eli export a computational role for **user-defined types**:

TypeDenotation: denotation of a user-defined type. The Type attribute of the symbol inheriting this role is set to a new definition table key by a module computation.

```
RULE: Type ::= ArrayType COMPUTE
   Type.Type = ArrayType.Type;
END;

SYMBOL ArrayType INHERITS TypeDenotation END;

RULE: ArrayType ::= Type '[' ']' END;
```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Objectives:

Eli specification of language- and user-defined types

In the lecture:

Explain the computation and the use of the attributes

Assignments:

- Specify the SetLan types.

Classification of identifiers (1)

The type analysis modules export four **computational roles to classify identifiers**:

TypeDefDefId: definition of a type identifier. The designer must write a computation setting the Type attribute of this symbol to the type bound to the identifier.

TypeDefUseId: reference to a type identifier defined elsewhere. The Type attribute of this symbol is set by a module computation to the type bound to the identifier.

TypedDefId: definition of a typed identifier. The designer must write a computation setting the Type attribute of this symbol to the type bound to the identifier.

TypedUseId: reference to a typed identifier defined elsewhere. The Type attribute of this symbol is set by a module computation to the type bound to the identifier.

```
SYMBOL ClassBody INHERITS TypeDenotation END;
SYMBOL TypIdDef INHERITS TypeDefDefId END;
SYMBOL TypIdUse INHERITS TypeDefUseId END;

RULE: ClassDecl ::=
   OptModifiers 'class' TypIdDef OptSuper OptInterfaces ClassBody
COMPUTE TypIdDef.Type = ClassBody.Type;
END;

RULE: Type ::= TypIdUse COMPUTE
Type.Type = TypIdUse.Type;
END;
```


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Objectives:

Specifiy the roles of identifiers

In the lecture:

Explain the meaning of the roles

Assignments:

- Specify the SetLan types.

Classification of identifiers (2)

A declaration introduces typed entities; it plays the role **TypedDefinition**.

TypedDefId is the role for identifiers in a context where the type of the bound entity is determined

TypedUseId is the role for identifiers in a context where the type of the bound entity is used. The role **ChkTypedUseId** checks whether a type can be determined for the particular entity:

```
RULE: Declaration ::= Type VarNameDefs ';' COMPUTE
   Declaration.Type = Type.Type;
END;

SYMBOL Declaration INHERITS TypedDefinition END;
SYMBOL VarNameDef  INHERITS TypedDefId END;
SYMBOL VarNameUse  INHERITS TypedUseId, ChkTypedUseId END;
```


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Objectives:

Specifiy the roles of identifiers

In the lecture:

Explain the use of the roles

Assignments:

- Specify the SetLan types.

Type analysis for expressions (1): trees

An **expression** node represents a **program construct that yields a value**, and an **expression tree** is a subtree of the AST made up **entirely of expression nodes**. Type analysis within an expression tree is uniform; additional specifications are needed only at the roots and leaves.

The type analysis modules export the role **ExpressionSymbol** to classify expression nodes. It carries two attributes that characterize the node inheriting it:

Type: the type of value delivered by the node. It is always set by a module computation.

Required: the type of value required by the context in which the node appears.
The designer may write a computation to set this inherited attribute in the upper context if the node is the root of an expression tree; otherwise it is set by a module computation.

A node **n** is type-correct if (**n.Type acceptableAs n.Required**).

PrimaryContext expands to attribute computations that set the Type attribute of an expression tree leaf. The first argument must be the grammar symbol representing the expression leaf, which must inherit the **ExpressionSymbol** role. The second argument must be the result type of the expression leaf.

DyadicContext characterizes expression nodes with two operands. All four arguments of DyadicContext are grammar symbols: the result expression, the indication, and the two operand expressions. The second argument symbol must inherit the **OperatorSymbol** role; the others must inherit **ExpressionSymbol**.

Lecture Programming Languages and Compilers WS 2011/12 / Slide 608

Objectives:

Specifiy type analysis for expressions

In the lecture:

Explain the meaning of the roles

Assignments:

- Specify the typing of SetLan expressions.

Type analysis for expressions (2): leaves, operators

The nodes of expression trees are characterized by the roles **ExpressionSymbol** and **OperatorSymbol**. The tree contexts are characterized by the roles **PrimaryContext** (for leaf nodes), **MonadicContext**, **DyadicContext**, **ListContext** (for inner nodes), and **RootContext**:

```
SYMBOL Expr       INHERITS ExpressionSymbol END;
SYMBOL Operator   INHERITS OperatorSymbol END;
SYMBOL ExpIdUse   INHERITS TypedUseId END;

RULE: Expr ::= Integer COMPUTE
  PrimaryContext(Expr, intType);
END;
RULE: Expr ::= ExpIdUse COMPUTE
  PrimaryContext(Expr, ExpIdUse.Type);
END;
RULE: Expr ::= Expr Operator Expr COMPUTE
  DyadicContext(Expr[1], Operator, Expr[2], Expr[3]);
END;
RULE: Operator ::= '+' COMPUTE
  Operator.Indic = PlusOp;
END;
```


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Objectives:

Specifiy type analysis for expressions

In the lecture:

Explain the use of the roles

Assignments:

- Specify the typing of SetLan expressions.

Type analysis for expressions (3): Balancing

The conditional expression of C is an example of a **balance context**: The type of each branch (**Expr[3],Expr[4]**) has to be acceptable as the type of the whole conditional expression (**Expr[1]**):

```
RULE: Expr ::= Expr '?' Expr ':' Expr COMPUTE
  BalanceContext(Expr[1],Expr[3],Expr[4]);
END;
```

For the condition the pattern of slide PLaC-6.10 applies.

Balancing can also occur with an **arbitrary number of expressions** the type of which is balanced to yield a **common type at the root node** of that list, e.g. in

```
SYMBOL CaseExps INHERITS BalanceListRoot, ExpressionSymbolEND;
SYMBOL CaseExp  INHERITS BalanceListElem, ExpressionSymbolEND;

RULE: Expr ::= 'case' Expr 'in' CaseExps 'esac' COMPUTE
  TransferContext(Expr[1],CaseExps);
END;

RULE: CaseExps LISTOF CaseExp END;
RULE: CaseExp ::= Expr COMPUTE
  TransferContext(CaseExp,Expr);
END;
```


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Objectives:

Understand the notion of balancing of types

In the lecture:

Explain the use of the roles

Assignments:

- Specify the typing of SetLan expressions.

Type analysis for expressions (4)

Each **expression tree** has a **root**. The the RULE context in which the expression root in on the left-hand side specifies which requirements are imposed to the type of the expression. In the context of an assignment statement below, both occurrences of **`Expr`** are expression tree roots:

```
RULE: Stmt ::= Expr ':=' Expr COMPUTE
   Expr[2].Required = Expr[2].Type;
END;
```

In principle there are 2 different cases how the context states requirements on the type of the Expression root:

- no requirement: **`Expr.Required = NoKey;`** (can be omitted, is set by default)
  `Expr[1]` in the example above
- a specific type: **`Expr.Required =`** computation of some type**`;`**
  `Expr[2]` in the example above

Lecture Programming Languages and Compilers WS 2011/12 / Slide 610

Objectives:

Specifiy type analysis for expressions

In the lecture:

Explain the use of the role in the context of the root of an expression tree

Assignments:

- Specify the typing of SetLan expressions.

Operators of user-defined types

User-defined types may introduce operators that have operands of that type, e.g. the indexing operator of an array type:

```
SYMBOL ArrayType INHERITS OperatorDefs END;

RULE: ArrayType ::= Type '[' ']' COMPUTE
   ArrayType.GotOper =
      DyadicOperator(
         ArrayAccessor, NoOprName,
         ArrayType.Type, intType, Type.Type);
END;
```

The above introduces an operator definition that has the signature
`ArrayType.Type x intType -> Type.Type`
and adds it to the operator set of the indication **`ArrayAccessor`**.
The context below identifies an operator in that set, using the types of **`Expr[2]`** and **`Subscript`**. Instead of an operator nonterminal the **`Indication`** is given.

```
SYMBOL Subscript  INHERITS ExpressionSymbol END;
RULE: Expr ::= Expr '[' Subscript ']' COMPUTE
   DyadicContext(Expr[1], , Expr[2], Subscript);
   Indication(ArrayAccessor);
   IF(BadOperator,
      message(ERROR,"Invalid array reference",0,COORDREF));
END;
```


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Objectives:

Definition and application of user-defined operators

In the lecture:

Explain the use of the roles

Assignments:

- Specify the typing of SetLan expressions.

Functions and calls

Functions (methods) can be considered as operators having *n => 0* operands (parameters).
Roles: **OperatorDefs**, **ListOperator**, and **TypeListRoot**:

```
SYMBOL MethodHeader INHERITS OperatorDefs END;
SYMBOL Parameters INHERITS TypeListRoot END;

RULE: MethodHeader ::=
   OptModifiers Type FctIdDef '(' Parameters ')' OptThrows COMPUTE
   MethodHeader.GotOper =
      ListOperator(
            FctIdDef.Key, NoOprName,
            Parameters, Type.Type);
END;
```

A call of a function (method) with its arguments is then considered as part of an expression tree. The function name (**FctIdUse**) contributes the **Indication**:

```
SYMBOL Arguments INHERITS OperandListRoot END;
RULE: Expr ::= Expr '.' FctIdUse '(' Arguments ')' COMPUTE
   ListContext(Expr[1], , Arguments);
   Indication(FctIdUse.Key);
   IF(BadOperator,message(ERROR, "Not a function", 0, COORDREF));
END;
```

The specification allows for overloaded functions.

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Objectives:

Functions considered as user-defined n-ary operators

In the lecture:

Explain the use of the roles

Assignments:

- Specify the typing of SetLan expressions.

Type equivalence: name equivalence

Two types *t* and *s* are **name equivalent** if their names *tn* and *sn* are the same or if *tn* is defined to be *sn* or sn defined to be *tn*. An anonymous type is different from any other type.

Name equivalence is applied for example in **Pascal**, and for classes and interfaces in **Java**.

```
type  a = record x: char; y: real end;
      b = record x: char; y: real end;
      c = b;

      e = record x: char; y: ↑ e end;
      f = record x: char; y: ↑ g end;
      g = record x: char; y: ↑ f end;


var   s, t: record x: char; y: real end;
      u: a; v: b; w: c;
      k: e; l: f; m: g;
```

Which types are equivalent?
The value of which variable may be assigned to which variable?

Lecture Programming Languages and Compilers WS 2011/12 / Slide 610c

Objectives:

Understand name equivalence

In the lecture:

Explain the examples

Questions:

Answer the questions on the slide.

Type equivalence: structural equivalence

In general, two types *t* and *s* are **structurally equivalent** if their definitions become the same when all type identifiers in the definitions of *t* and in *s* are recursively substituted by their definitions. (That may lead to infinite trees.)
Structural equivalence is applied for example in **Algol-68**, and for array types in **Java**.

The example of the previous slide is interpreted under structural equivalence:

```
type  a = record x: char; y: real end;
      b = record x: char; y: real end;
      c = b;

      e = record x: char; y: ↑ e end;
      f = record x: char; y: ↑ g end;
      g = record x: char; y: ↑ f end;


var   s, t: record x: char; y: real end;
      u: a; v: b; w: c;
      k: e; l: f; m: g;
```

Which types are equivalent?
The value of which variable may be assigned to which variable?

Algorithms determine structural equivalence by decomposing the whole set of types into maximal partitions, which each contain only equivalent types.

Lecture Programming Languages and Compilers WS 2011/12 / Slide 610d

Objectives:

Understand structural equivalence

In the lecture:

Explain the examples

Questions:

Answer the questions on the slide.

Type analysis for object-oriented languages (1)

Class hierarchy is a type hierarchy:

implicit type coercion: class -> super class
explicit type cast: class -> subclass

Variable of class type may contain
an object (reference) of its subclass

```
Circle k = new Circle (...);

GeometricShape f = k;

k = (Circle) f;
```

Analyze dynamic method binding; try to decide it statically:

static analysis tries to further restrict the run-time type:

```
GeometricShape f;...; f = new Circle(...);...; a = f.area();
```


Lecture Programming Languages and Compilers WS 2011/12 / Slide 611

Objectives:

Understand classes as types

In the lecture:

Explain

- class hierarchy - type coercion;
- type checking for dynamically bound method calls with compile time information,
- predict the runtime class of objects

Questions:

- Why can it be useful for the compiler to know the bound method exactly?

Type analysis for object-oriented languages (2)

Check signature of overriding methods:

calls must be **type safe**

Java requires the **same signature**

weaker requirements would be sufficient (*contra variant parameters*, language Sather):

call of dynamically bound method:

```
a = x.m (p);
```

Variable: `X x; A a; P p; C c; B b;`

super class
```
class X { C m  (Q q) { use of q;... return c; } }
```

subclass
```
class Y { B m  (R r) { use of r;... return b; } }
```

Language Eiffel requires **covariant parameter types**: type unsafe!

Lecture Programming Languages and Compilers WS 2011/12 / Slide 612

Objectives:

Understand classes as types

In the lecture:

Explain

- type checking for dynamically bound method calls with compile time information:
- x has type X,
- signature of m in X,
- m in Y safely overrides m in X;

Questions:

- Why would overridden methods not be type safe if they had "covariant" parameters (all 3 arrows between the classes X and Y would point up)? That is the situation in Eiffel.

Type analysis for functional languages (1)

Static typing and type checking without types in declarations

Type inference: Types of program entities are inferred from the context where they are used

Example in ML:

```
fun choice (cnt, fct) =
  if fct cnt then cnt else cnt - 1;
    (i)          (ii)     (iii)
```

describe the types of entities using type variables:

```
cnt:    'a,
fct:    'b->'c,
choice: ('a * ('b->'c)) -> 'd
```

form equations that describe the uses of typed entities

```
(i)    'c= bool
(i)    'b= 'a
(ii)   'd= 'a
(iii)  'a= int
```

solve the system of equations:

```
choice: (int * (int->bool)) -> int
```


Lecture Programming Languages and Compilers WS 2011/12 / Slide 613

Objectives:

Understand type inference

In the lecture:

Explain how types are computed using the types of operations and program entities without having typed declarations

Questions:

- How would type inference find type errors?

Type analysis for functional languages (2)

Parametrically polymorphic types: types having type parameters

Example in ML:

```
fun map (l, f) =
          if null l
          then nil
          else (f (hd l)) :: map (tl l, f)
```

polymorphic signature:

```
map: ('a list * ('a -> 'b)) -> 'b list
```

Type inference yields **most general type** of the function,
such that all uses of entities in operations are correct;

i. e. **as many unbound type parameters as possible**

calls with different concrete types, consistently substituted for the type parameter:

```
map([1,2,3], fn i => i*i)         'a = int, 'b = int
map([1,2,3], even)                'a = int, 'b = bool
map([1,2,3], fn i =(i,i))         'a = int, 'b = ('a*'a)
```


Lecture Programming Languages and Compilers WS 2011/12 / Slide 614

Objectives:

Understand polymorphic types

In the lecture:

- Explain analysis with polymorphic types.
- Explain the difference of polymorphic types and generic types from the view of type analysis.

Semantic error handling

Design rules:

Error reports are to be **related to the source code**:

- Any explicit or implicit **requirement of the language definition** needs to be checked by an operation in the tree, e. g.
  `if (IdUse.Bind == NoBinding) message (...)`
- Checks have to be associated to the **smallest relevant context** yields precise source position for the report; information is to be propagated to that context. **wrong**: „some arguments have wrong types“
- **Meaningfull error reports. wrong**: „type error“
- **Different reports for different violations**; do not connect symptoms by **or**

All **operations specified for the tree are executed**, even if errors occur:

- introduce **error values**, e. g. **`NoKey, NoType, NoOpr`**
- operations that **yield results** have to yield a reasonable one in case of error,
- operations have to accept **error values as parameters**,
- **avoid messages for avalanche errors** by suitable extension of relations, e. g. every type is compatible with **`NoType`**

Lecture Programming Languages and Compilers WS 2011/12 / Slide 615

Objectives:

Design rules for error handling

In the lecture:

Explanations and examples

Suggested reading:

Kastens / Übersetzerbau, Section 6.3

7. Specification of Dynamic Semantics

The **effect of executing a program** is called its dynamic semantics. It can be described by **composing the effects** of executing the elements of the program, according to its **abstract syntax**. For that purpose the **dynamic semantics of executable language constructs** are specified.

Informal specifications are usually formulated in terms of an abstract machine, e. g.

> *Each **variable has a storage cell**, suitable to store values of the type of the variable. An **assignment v := e** is **executed** by the following steps: determine the storage cell of the variable v, **evaluate the expression** e yielding a value x, an storing x in the storage cell of v.*

The effect of common operators (like arithmetic) is usually not further defined (pragmatics).

The effect of an **erroneous program construct is undefined**. An erroneous program is not executable. The language specification often does not explicitly state, what happens if an erroneous program construct is executed, e. g.

> *The **execution of an input statement is undefined** if the next value of the the input is **not a value of the type** of the variable in the statement.*

A **formal calculus** for specification of dynamic semantics is **denotational semantics**.
It **maps language constructs to functions**, which are then **composed** according to the abstract syntax.

Lecture Programming Languages and Compilers WS 2010/11 / Slide 701

Objectives:

Introduction of the topic

In the lecture:

The topics on the slide are explained.

Denotational semantics

Formal calculus for specification of dynamic semantics.

The executable constructs of the **abstract syntax are mapped on functions**, thus defining their effect.

For a given structure tree the functions associated to the tree nodes are **composed** yielding a semantic function of the whole program - **statically**!

That calculus allows to

- **prove dynamic properties** of a program formally,
- reason about the **function of the program** - rather than about is operational execution,
- reason about **dynamic properties of language constructs** formally.

A **denotational specification** of dynamic semantics of a programming language consists of:

- specification of **semantic domains**: in imperative languages they model the program state
- a function **E that maps all expression constructs** on semantic functions
- a function **C that maps all statement contructs** on semantic functions

Lecture Programming Languages and Compilers WS 2010/11 / Slide 702

Objectives:

Introduction of a calculus for formal modelling semantics

In the lecture:

Give an overview on the appoach; the roles of

- semantic domains (cf. lecture on Modelling),
- mappings E and C

Semantic domains

Semantic domains describe the **domains and ranges of the semantic functions** of a particular language. For an imperative language the central semantic domain describes the **program state**.

Example: semantic domains of a very **simple imperative language**:

State	**= Memory × Input × Output**	program state
Memory	**= Ident → Value**	storage
Input	**= Value***	the input stream
Output	**= Value***	the output stream
Value	**= Numeral | Bool**	legal values

Consequences for the language specified using these semantic domains:

- The language can allow **only global variables**, because a 1:1-mapping is assumed between identifiers and storage cells. In general the storage has to be modelled:

  Memory = Ident → (Location → Value)

- **Undefined values** and an **error state** are not modelled; hence, behaviour in **erroneous cases** and **exeption handling** can not be specified with these domains.

Objectives:

Understand a simple example

In the lecture:

Explain

- the domains of the example,
- the consequences.

Mapping of expressions

Let **Expr** be the set of all **constructs of the abstract syntax** that represent expressions, then the function **E** maps **Expr** on functions which describe **expression evaluation**:

E: Expr → (State → Value)

In this case the semantic expression functions **compute a value in a particular state**. **Side-effects** of expression evaluation can not be modelled this way. In that case the evaluation function had to return a potentially changed state:

E: Expr → (State → (State × Value))

The mapping **E** is **defined by enumerating the cases of the abstract syntax** in the form

E[abstract syntax construct **]** state **=** functional expression
E[X] **s** **= F s**

for example:

```
E [e1 + e2] s = (E [e1] s) + (E [e2] s)
...
E [Number] s = Number
E [Ident] (m, i, o) = m Ident
```

(the memory map applied to the identifier)

Objectives:

Understand the expression functions

In the lecture:

The expression functions on the slide are explained using the given examples.

Questions:

- How would a particular order of evaluation of operands be specified?

Mapping of statements

Let **Command** be the set of all **constructs of the abstract syntax** that represent statements, then the function **C** maps **Command** on functions which describe **statement execution:**

C: Command → (State → State)

In this case the semantic statement functions **compute a state transition.**
Jumps and labels in statement execution can not be modelled this way. In that case an additional functional argument would be needed, which models the continuation after execution of the specified construct, **continuation semantics**.

The mapping **C** is defined by enumerating the cases of the abstract syntax in the form

C[abstract syntax construct**]** state **=** functional expression
C[X] s = F s

for example:

```
C [stmt1; stmt2] s = (C [stmt2] o C [stmt1]) s
```
function composition

```
C [v := e] (m, i, o) = (M [(E [e] (m, i, o)) / v], i, o)
```
e is evaluated in the given state and the memory map is changed at the cell of v

```
C [if ex then stmt1 else stmt2] s = E[ex]s -> C[stmt1]s, C[stmt2]s
C [while ex do stmt] s =
   E[ex]s -> (C[while ex do stmt] o C[stmt])s, s
...
```


Lecture Programming Languages and Compilers WS 2010/11 / Slide 705

Objectives:

Understand the statement functions

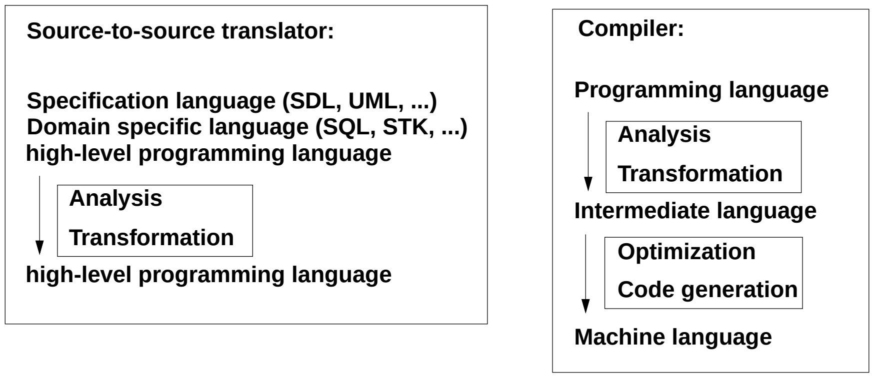
In the lecture:

The domains and functions are explained:

- composition of functions,
- update of the memory,
- alternative functions,
- recursive definition of while-semantics

8. Source-to-source translation

Source-to-source translation:
Translation of a **high-level source language** into a **high-level target language**.



Transformation task:

input: structure tree + properties of constructs (attributes), of entities (def. module)

output:**target tree** (attributes) in textual representation

Lecture Programming Languages and Compilers WS 2010/11 / Slide 801

Objectives:

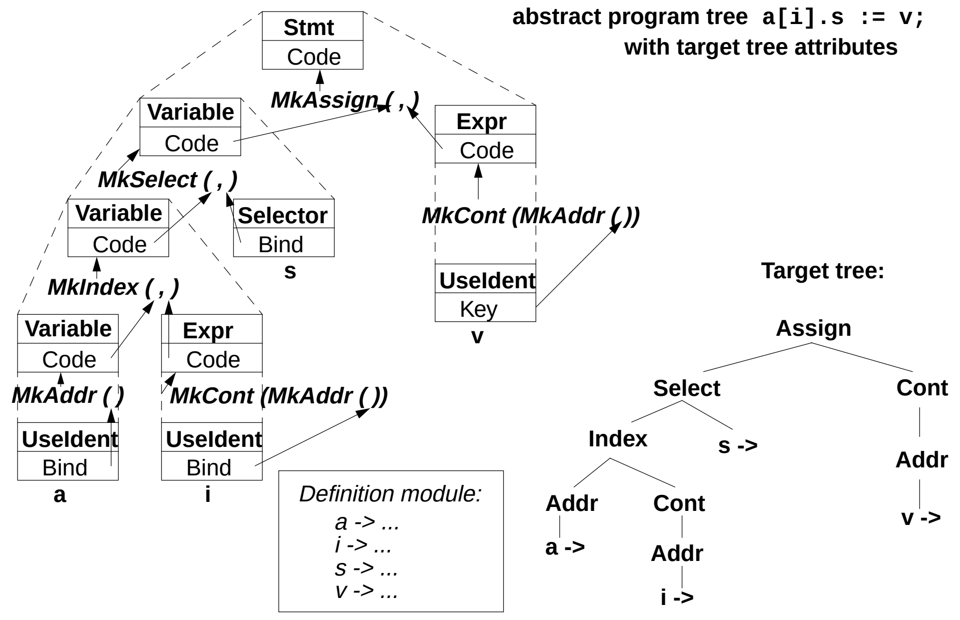
Understand the task

In the lecture:

Explain

- the notion,
- characteristics of source languages,
- comparison with compilers,
- target trees.

Example: Target tree construction



Lecture Programming Languages and Compilers WS 2010/11 / Slide 802

Objectives:

Recognize the principle of target tree construction

In the lecture:

Explain the principle using the example. Refer to the AG on PLaC-8.3.

Attribute grammar for target tree construction

```
RULE: Stmt ::= Variable ':=' Expr            COMPUTE
    Stmt.Code = MkAssign (Variable.Code, Expr.Code);
END;
RULE: Variable ::= Variable '.' Selector    COMPUTE
    Variable[1].Code = MkSelect (Variable[2].Code, Selector.Bind);
END;
RULE: Variable ::= Variable '[' Expr ']'     COMPUTE
    Variable[1].Code = MkIndex (Variable[2].Code, Expr.Code);
END;
RULE: Variable ::= UseIdent                  COMPUTE
    Variable.Code = MkAddr (UseIdent.Bind);
END;
RULE: Expr ::= UseIdent                      COMPUTE
    Expr.Code = MkCont (MkAddr (UseIdent.Bind));
END;
```

Lecture Programming Languages and Compilers WS 2010/11 / Slide 803

Objectives:

Attribute grammar specifies target tree construction

In the lecture:

Explain using the example of PLaC-8.2

Generator for creation of structured target texts

Tool PTG: Pattern-based Text Generator

Creation of structured texts in arbitrary languages. Used as computations in the abstract tree, and also in arbitrary C programs. Principle shown by examples:

1. Specify output pattern with insertion points:

```
ProgramFrame:   $
                "void main () {\n"
                $
                "}\n"

Exit:           "exit (" $ int ");\n"

IOInclude:      "#include <stdio.h>"
```

2. PTG generates a function for each pattern; calls produce target structure:

```
PTGNode a, b, c;
a = PTGIOInclude ();
b = PTGExit (5);
c = PTGProgramFrame (a, b);
```

correspondingly with attribute in the tree

3. Output of the target structure:

`PTGOut (c);` or `PTGOutFile ("Output.c", c);`

Lecture Programming Languages and Compilers WS 2010/11 / Slide 804

Objectives:

Principle of producing target text using PTG

In the lecture:

Explain the examples

Questions:

- Where can PTG be applied for tasks different from that of translators?

PTG Patterns for creation of HTML-Texts

concatenation of texts:
```
Seq:          $ $
```

large heading:
```
Heading:      "<H1>" $1 string "</H1>\n"
```

small heading:
```
Subheading:   "<H3>" $1 string "</H3>\n"
```

paragraph:
```
Paragraph:    "<P>\n" $1
```

Lists and list elements:
```
List:         "<UL>\n" $ "</UL>\n"
Listelement:  "<LI>" $ "</LI>\n"
```

Hyperlink:
```
Hyperlink:    "<A HREF=\"" $1 string "\">" $2 string "</A>"
```

Text example:

```
<H1>My favorite travel links</H1>
<H3>Table of Contents</H3>
<UL>
<LI> <A HREF="#position_Maps">Maps</A></LI>
<LI> <A HREF="#position_Train">Train</A></LI>
</UL>
```


Lecture Programming Languages and Compilers WS 2010/11 / Slide 805

Objectives:

See an application of PTG

In the lecture:

Explain the patterns

Questions:

- Which calls of pattern functions produce the example text given on the slide?

PTG functions build the target tree (1)

Attributes named Code propagate target sub-trees

Write the target text to a file

```
ATTR Code: PTGNode;

SYMBOL Program COMPUTE

   PTGOutFile
      (CatStrStr (SRCFILE, ".java"),
         PTGFrame
            (CONSTITUENTS Declaration.Code
             WITH (PTGNode, PTGSeq, IDENTICAL, PTGNull),

             CONSTITUENTS Statement.Code SHIELD Statement
             WITH (PTGNode, PTGSeq, IDENTICAL, PTGNull)));

END;
```

PTG pattern with 2 arguments

Access 2 target sub-trees

Lecture Programming Languages and Compilers WS 2010/11 / Slide 806

Objectives:

Understand the use of PTG functions for target text creation

In the lecture:

Explain the use of PTG functions in root context.

PTG functions build the target tree (2)

```
RULE: Declaration ::= Type VarNameDefs ';' COMPUTE
   Declaration.Code =
      CONSTITUENTS VarNameDef.Code
      WITH (PTGNode, PTGSeq, IDENTICAL, PTGNull);
END;

SYMBOL VarNameDef COMPUTE
   SYNT.Code =
      IF (EQ (INCLUDING TypedDefinition.Type, intType),
         PTGIntDeclaration (SYNT.NameCode),
      ...
      PTGNULL))));
END;
```


Lecture Programming Languages and Compilers WS 2010/11 / Slide 807

Objectives:

Understand the use of PTG functions for target text creation

In the lecture:

Explain the use of PTG functions to compose the target tree.

Generate and store target names

```
SYMBOL VarNameDef: NameCode: PTGNode;

SYMBOL VarNameDef COMPUTE
  SYNT.NameCode =
    PTGAsIs
      (StringTable
        (GenerateName (StringTable (TERM))));

  SYNT.GotTgtName =
    ResetTgtName (THIS.Key, SYNT.NameCode);
END;

SYMBOL VarNameUse COMPUTE
  SYNT.Code = GetTgtName (THIS.Key, PTGNULL)
    <- INCLUDING Program.GotTgtName;
END;

SYMBOL Program COMPUTE
  SYNT.GotTgtName =
    CONSTITUENTS VarNameDef.GotTgtName;
END;
```

Create a new name from the source name

Store the name in the definition module

Access the name from the definition module

All names are stored before any is accessed

Lecture Programming Languages and Compilers WS 2010/11 / Slide 808

Objectives:

Understand how to store generated names

In the lecture:

Explain the use of PTG and PDL functions.

9. Domain Specific Languages (DSL)

(under construction)

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Objectives:

to be done

In the lecture:

10. Summary
Questions to check understanding

1. Language properties - compiler tasks

1.1. Associate the compiler tasks to the levels of language definition.

1.2. Describe the structure of compilers and the interfaces of the central phases.

1.3. For each phase of compiler frontends describe its task, its input, its output.

1.4. For each phase of compiler frontends explain how generators can contribute to its implementation.

1.5. What specifications do the generators of (1.4) take and what do they generate?

1.6. What data structures are used in each of the phases of compiler frontends?

1.7. Give examples for feedback between compiler phases.

1.8. Java is implemented differently than many other languages, e.g. C++, what is the main difference?

Objectives:

Questions for repetition

In the lecture:

Answer some questions for demonstration

Questions:

More questions can be found along with the slides of this topic

2. Symbol specification and lexical analysis

2.1. Which formal methods are used to specify tokens?

2.2. How are tokens represented after the lexical analysis phase?

2.3. Which information about tokens is stored in data structures?

2.4. How are the components of the token representation used in later phases?

2.5. Describe a method for the construction of finite state machines from syntax diagrams.

2.6. What does the rule of the longest match mean?

2.7. Compare table-driven and directly programmed automata.

2.8. Which scanner generators do you know?

Objectives:

Questions for repetition

In the lecture:

Answer some questions for demonstration

Questions:

More questions can be found along with the slides of this topic

3. Context-free grammars and syntactic analysis

3.1. Which roles play concrete and abstract syntax for syntactic analysis?

3.2. Describe the underlying principle of recursive descent parsers. Where is the stack?

3.3. What is the grammar condition for recursive descent parsers?

3.4. Explain systematic grammar transformations to achieve the LL(1) condition.

3.5. Why are bottom-up parsers in general more powerful than top-down parsers?

3.6. Which information does a state of a LR(1) automaton represent?

3.7. Describe the construction of a LR(1) automaton.

3.8. Which kinds of conflicts can an LR(1) automaton have?

3.9. Characterize LALR(1) automata in contrast to those for other grammar classes.

3.10. Describe the hierarchy of LR and LL grammar classes.

3.11. Which parser generators do you know?

3.12. Explain the fundamental notions of syntax error handling.

3.13. Describe a grammar situation where an LR parser would need unbounded lookahead.

3.14. Explain: the syntactic structure shall reflect the semantic structure.

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Objectives:

Questions for repetition

In the lecture:

Answer some questions for demonstration

Questions:

More questions can be found along with the slides of this topic

4. Attribute grammars and semantic analysis

4.1. What are the fundamental notions of attribute grammars?

4.2. Under what condition is the set of attribute rules complete and consistent?

4.3. Which tree walk strategies are related to attribute grammar classes?

4.4. What do visit-sequences control? What do they consist of?

4.5. What do dependence graphs represent?

4.6. What is an attribute partition; what is its role for tree walking?

4.7. Explain the LAG(k) condition.

4.8. Describe the algorithm for the LAG(k) check.

4.9. Describe an AG that is not LAG(k) for any k, but is OAG for visit-sequences.

4.10. Which attribute grammar generators do you know?

4.11. How is name analysis for C scope rules specified?

4.12. How is name analysis for Algol scope rules specified?

4.13. How is the creation of target trees specified?

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Objectives:

Questions for repetition

In the lecture:

Answer some questions for demonstration

Questions:

More questions can be found along with the slides of this topic

5. Binding of names

5.1. How are bindings established explicitly and implicitly?

5.2. Explain: consistent renaming according to scope rules.

5.3. What are the consequences if defining occurence before applied occurence is required?

5.4. Explain where multiple definitions of a name could be reasonable?

5.5. Explain class hierarchies with respect to static binding.

5.6. Explain the data structure for representing bindings in the environment module.

5.7. How is the lookup of bindings efficiently implemented?

5.8. How is name analysis for C scope rules specified by attribute computations?

5.9. How is name analysis for Algol scope rules specified by attribute computations?

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Objectives:
Questions for repetition

In the lecture:
Answer some questions for demonstration

Questions:
More questions can be found along with the slides of this topic

6. Type specification and analysis

6.1. What does „statically typed“ and „strongly typed“ mean?

6.2. Distinguish the notions „type“ and „type denotation“?

6.3. Explain the taxonomy of type systems.

6.4. How is overloading and coercion specified in Eli?

6.5. How is overloading resolved?

6.6. Distinguish Eli’s four identifier roles for type analysis?

6.7. How is type analysis for expressions specified in Eli?

6.8. How is name equivalence of types defined? give examples.

6.9. How is structural equivalence of types defined? give examples.

6.10. What are specific type analysis tasks for object-oriented languages?

6.11. What are specific type analysis tasks for functional languages?

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Objectives:
Questions for repetition

In the lecture:
Answer some questions for demonstration

Questions:
More questions can be found along with the slides of this topic

7. , 8. Dynamic semantics and transformation

7.1. What are denotational semantics used for?

7.2. How is a denotational semantic description structured?

7.3. Describe semantic domains for the denotational description of an imperative language.

7.4. Describe the definition of the functions E and C for the denotational description of an imperative language.

7.5. How is the semantics of a while loop specified in denotational semantics?

7.6. How is the creation of target trees specified by attribute computations?

7.7. PTG is a generator for creating structured texts. Explain its approach.

Objectives:

Questions for repetition

In the lecture:

Answer some questions for demonstration

Questions:

More questions can be found along with the slides of this topic