# Compiler I

## (dt. Übersetzer I)

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## Winter 2001/2002





## Objectives

The participants are taught to

- understand **fundamental techniques** of language implementation,
- use **generating tools and standard solutions**,
- understand compiler construction as a systematic combination of **algorithms, theories** and **software engineering** methods for the solution of a **precisely specified task**,
- apply compiler techniques for languages **other than programming languages**.

Forms of teaching:

**Lectures**

**Tutorials**

**Homeworks**

**Exercises**

**Running project**





## Lectures in English

Some agreements about giving lectures in English:

- I'll speak English unless someone asks me to explain something in German.
- Stop me or slow me down whenever you get lost.
- I don't speak as well as a native speaker; but I'll do my best ...
- You may ask questions and give answers in English or in German.
- I'll prepare the slides in English. A German version is available.
- You'll have to learn to speak about the material in at least one of the two languages.
- You may vote which language to be used in the tutorials.
- You may chose German or English for the oral exam.





## Syllabus

| Week | Chapter | Topic |
|---|---|---|
| 1 | **Introduction** | Compiler tasks |
| 2 | | Compiler structure |
| 3 | **Lexical analysis** | Scanning, token representation |
| 4 | **Syntactic analysis** | Recursive decent parsing |
| 5 | | LR Parsing |
| 6 | | Parser generators |
| 7 | | Grammar design |
| 8 | **Semantic analysis** | Attribute grammars |
| 9 | | Attribute grammar specifications |
| 10 | | Name analysis |
| 11 | | Type analysis |
| 12 | **Transformation** | Intermediate language, target trees |
| 13 | | Target texts |
| 14 | **Synthesis** | Overview |
| 15 | **Summary** | |

# Prerequisites

| from Lecture | Topic | here needed for |
|---|---|---|
| Foundations of Programming Languages: | | |
| | 4 levels of language properties | Compiler tasks, compiler structure |
| | Context-free grammars | Syntactic analysis |
| | Scope rules | Name analysis |
| | Data types | Type analysis |
| | Lifetime, runtime stack | Storage model, code generation |
| Modeling: | | |
| | Finite automata | Lexical analysis |
| | Context-free grammars | Syntactic analysis |



# References

Material for this course **Compiler I**: http://www.uni-paderborn.de/cs/ag-kastens/compi
in German **Übersetzer I** (1999/2000): http://www.uni-paderborn.de/cs/ag-kastens/uebi
in English **Compiler II**: http://www.uni-paderborn.de/cs/ag-kastens/uebii

**Modellierung**: http://www.uni-paderborn.de/cs/ag-kastens/model
**Grundlagen der Programmiersprachen**: http://www.uni-paderborn.de/cs/ag-kastens/gdp


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

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

W. M. Waite, G. Goos: **Compiler Construction**, Springer-Verlag, 1983

R. Wilhelm, D. Maurer: **Übersetzerbau - Theorie, Konstruktion, Generierung**, Springer-Verlag, 1992

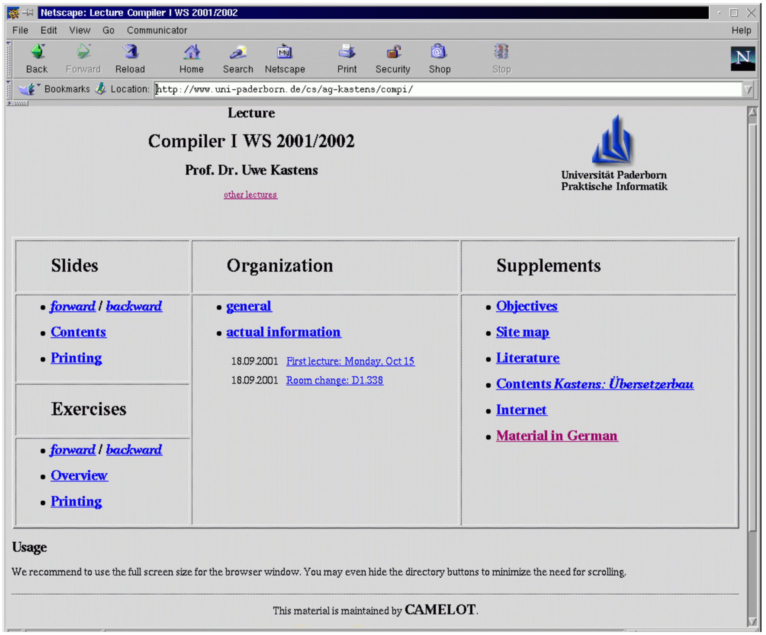
A. Aho, R. Sethi, J. D. Ullman: **Compilers - Principles, Techniques and Tools**, Addison-Wesley, 1986

A. W. Appel: **Modern Compiler Implementation in C**, Cambridge University Press, 1997
(available for Java and for ML, too)





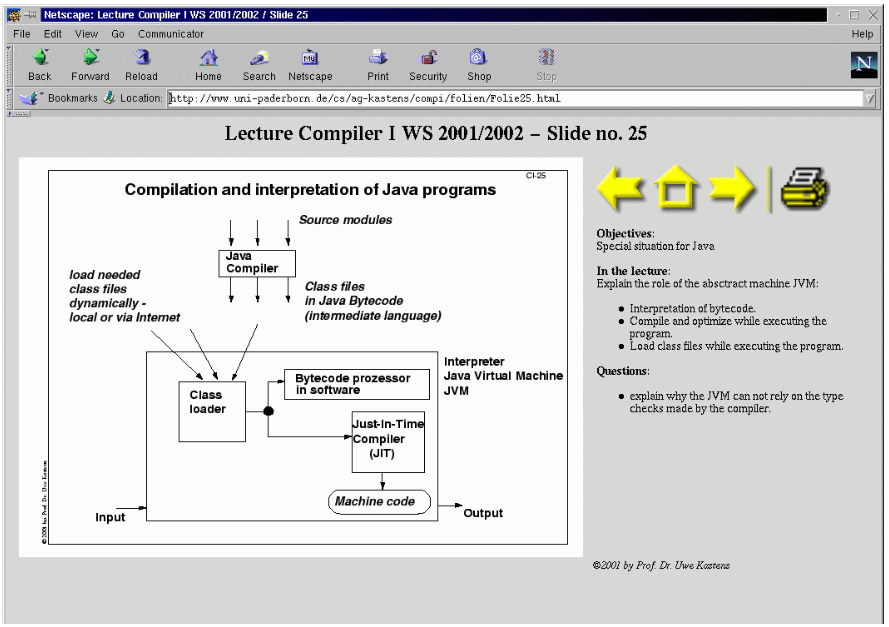

# Course material in the Web








# Commented slide in 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**<br>C++ | **Machine language**<br>Sparc code |
| **Programming language**<br>Java | **Abstract machine**<br>Java Bytecode |
| **Programming language**<br>C++ | **Programming language (source-to-source)**<br>C |
| **Application language**<br>LaTeX<br>Data base language (SQL) | **Application language**<br>HTML<br>Data base system calls |





# 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
```





# 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
```





# Languages for specification and modeling

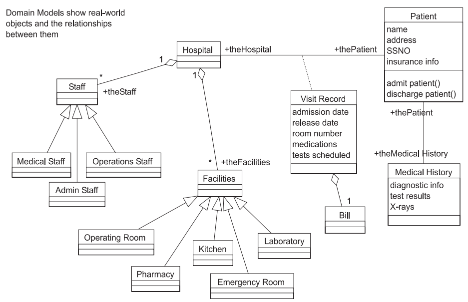
SDL (CCITT)
Specification and Description Language:

```
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:



# 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**
- **Report generator for bibliographies:**

```
string name =   InString "Which author?";
int since =     InInt "Since which year?";
int cnt = 0;

"\nPapers of ", name, " since ", since, ":\n";
[ SELECT name <= Author && since <= Year;
  cnt = cnt + 1;
  Year, "\t", Title, "\n";
]
"\n", name, " published ", cnt, "papers.\n";
```

U. Kastens: Construction of Application Generators Using Eli, Workshop on Compiler Techniques for Application Domain Languages ..., Linköping, April 1996





# 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

**Program languages as target languages:**

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

**=> Compiler task: Source-to-source compilation**





# Semester project as running example

## A Structure Generator

We are going to develop a tool that implements **record structures**. In particular, the structure generator takes a set of **record descriptions**. Each specifies a **set of named and typed fields**. For each record a **Java class** declaration is to be generated. It contains a constructor method and access methods for the specified record fields.

The tool will be used in an environment where field description are created by other tools, which for example analyze texts for the occurrence of certain phrases. Hence, the descriptions of fields may occur in arbitrary order, and the same field may be described more than once. The structure generator **accumulates the field descriptions** such that for each record a single class declaration is generated which has all fields of that record.

Design a **domain specific language**.

Implement an **application generator** for it.

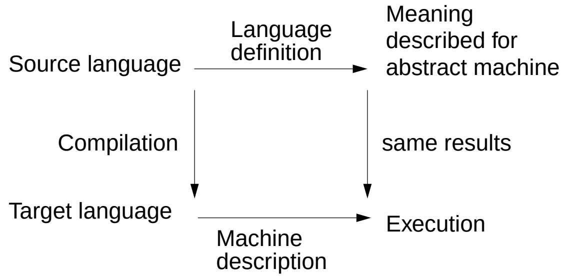
Apply all **techniques of the course** that are useful for the task.





# Meaning preserving transformation

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




A **meaning** is defined only for **correct** programs. Compiler task: Error handling

The compiler analyses **static** properties of the program at **compile time,**
e. g. definitions of Variables, types of expressions. Decides: Is the program **compilable?**

**Dynamic** properties of the program are checked at **runtime,**
e. g. indexing of arrays. Decides: Is the program **executable?**

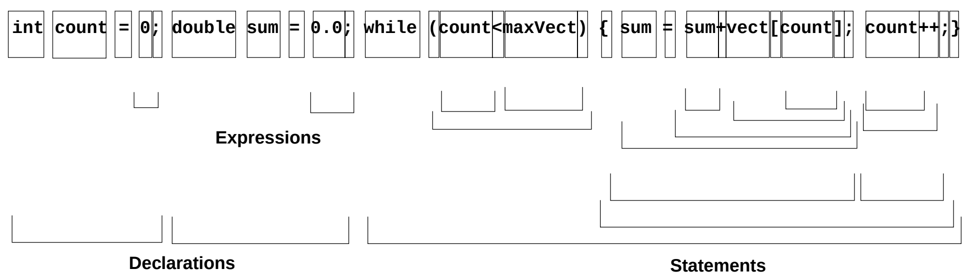
But in Java: Compilation of bytecode at runtime, just in time compilation (JIT)

# Example: Tokens and structure

*Character sequence*

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

*Tokens*



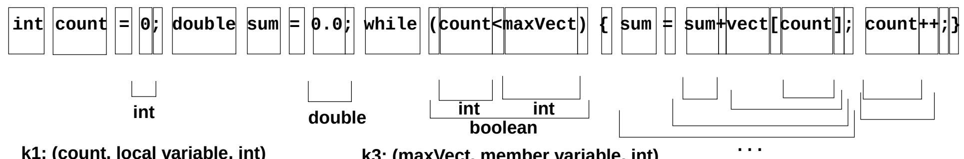

*Structure*





# Example: Names, types, generated code

*Tokens*




k1: (count, local variable, int)
k2: (sum, local variable, double)
k3: (maxVect, member variable, int)
k4: (vect, member variable, double array)

*Names and types*

*generated Bytecode*

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





# Language definition - Compiler task

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

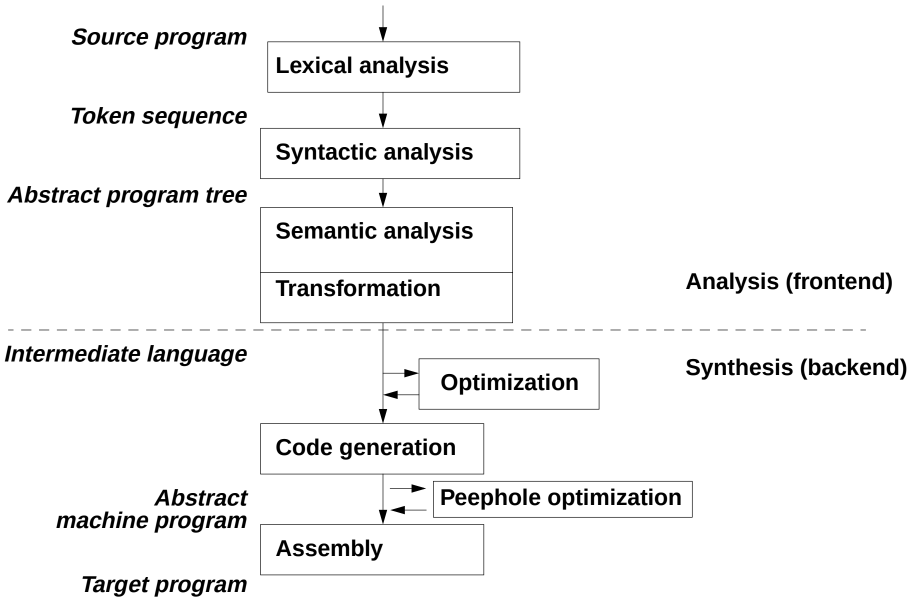




# Compiler tasks

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

# Compiler structure and interfaces








# Software qualities of the compiler

- **Correctness** Translate correct programs correctly. Reject wrong programs and give 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** Give a reasonable reaction on every input





# Strategies for compiler construction

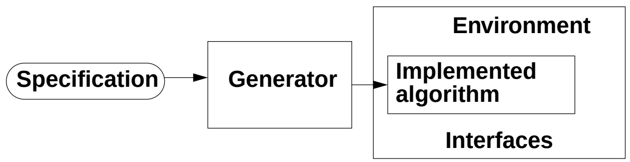
- **Obey exactly to the language definition**
- **Use generating tools**
- **Use standard components**
- **Apply standard methods**
- **Validate the compiler against a test suite**
- **Verify components of the compiler**





# Generators

**Pattern:**

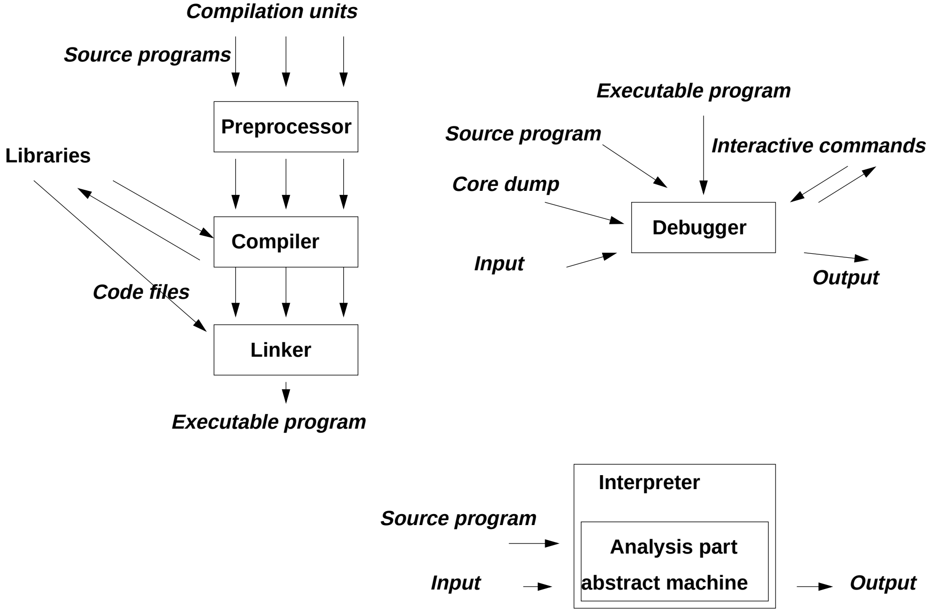



**Typical compiler tasks solved by generators:**

| | | |
|---|---|---|
| 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:**

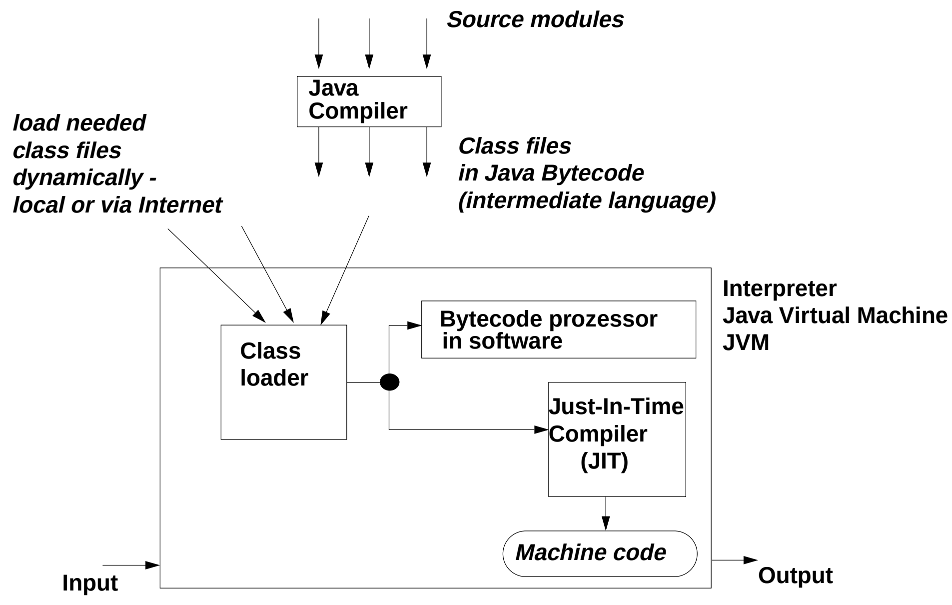
# Environment of compilers








# Compilation and interpretation of Java programs








# Lexical Analysis

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

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

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





# 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 |

## Specification of token notations
## Example: identifiers

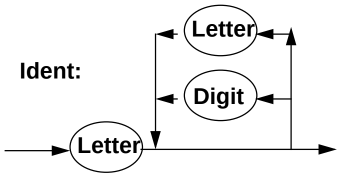
Ident = Letter (Letter | Digit)*

regular grammar ⟷ regular expression

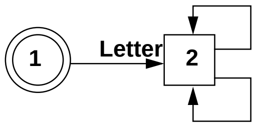
Ident ::= Letter X
X ::= Letter X
X ::= Digit X
X ::=

syntax diagram

Ident:




acceptor: finite state machine



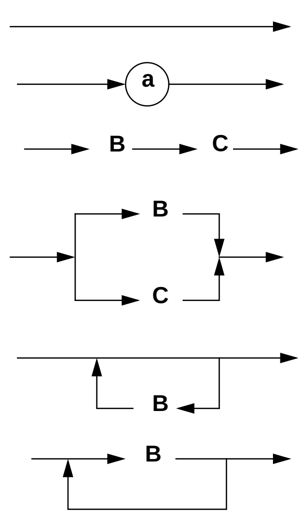





## Regular expressions mapped to syntax diagrams

**Transformation rules:**

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





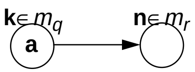
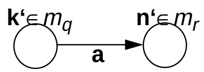



## Construction of deterministic finite state machines

| Syntax diagram | deterministic finite state machine |
|---|---|
| nodes, arcs | transitions, states |
| 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 — **initial state** *1*
3. **construct new sets of nodes (states)** and **transitions:** For a character *a* and a set $m_q$ containing node *k* create set $m_r$ with all nodes *n*, according to the following schema:

   for  create 



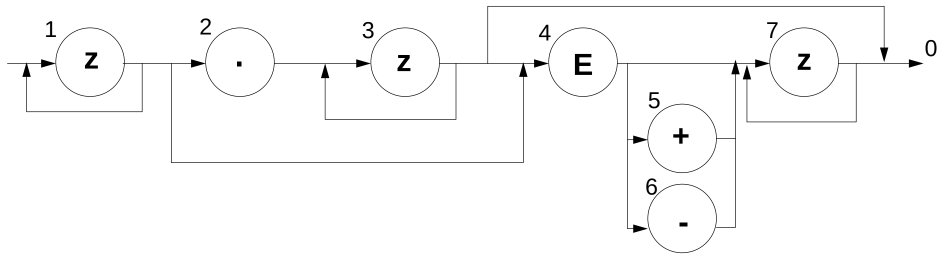
4. **repeat step 3** until no new sets of nodes can be created
5. a state *q* is a **final state** iff *0* is in $m_q$.



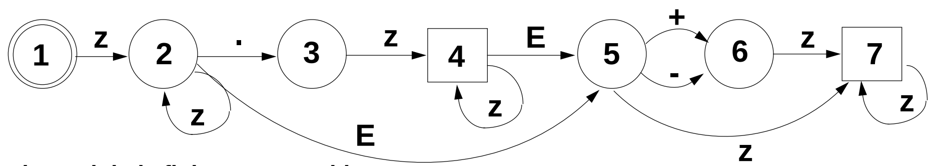


## Example: Floating point numbers in Pascal

**Syntax diagram**




| {1} | {1, 2, 4} | {3} | {3, 4, 0} | {5, 6, 7} | {7} | {7, 0} |
|---|---|---|---|---|---|---|
| z | z . E | z | z E | + - z | z | z |

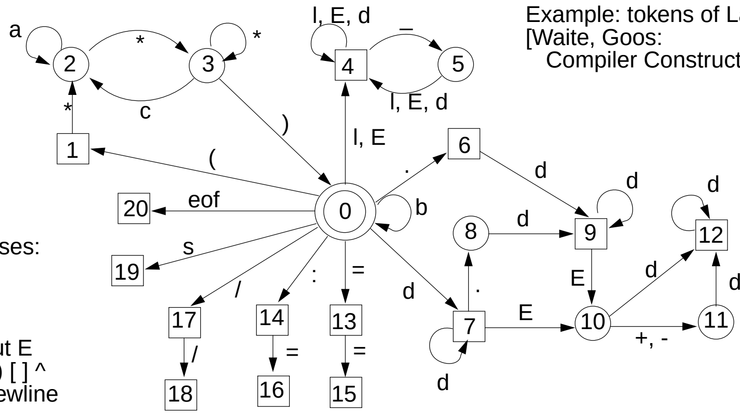



**deterministic finite state machine**

# Composition of token automata

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

- **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

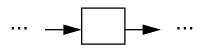




# Rule of the longest match

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.

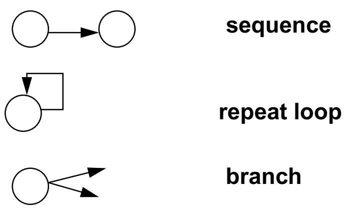
Check the concrete grammar for tokens that may occur adjacent!





# 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:**




- **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.





# 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

# 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;<br>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)<br>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 |





# Syntactic analysis

**Input: token sequence**

**Tasks:**
**Parsing**: construct derivation according to **concrete syntax**,
Tree construction according to **abstract syntax**,
Error handling (detection, 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.





# Concrete and abstract syntax

| **concrete syntax** | **abstract syntax** |
|---|---|
| context-free grammar | context-free grammar |
| defines the structure of source programs | defines abstract program trees |
| unambigous | usually ambiguous |
| specifies derivation and parser | translation phase is based on it |
| parser actions specify the ---> | tree construction |
| some chain productions only for syntactic purpose<br>`Expr ::= Fact` have no action | keep only semantically relevant ones<br>no node created |

symbols of syntactic chain productions comprised in symbol classes `Exp={Expr,Fact}`

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

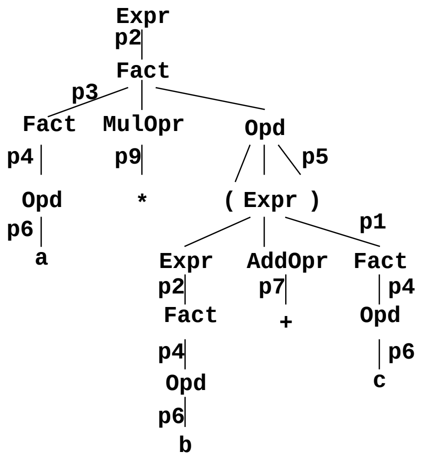
| | |
|---|---|
| terminal symbols | keep only semantically relevant ones<br>as tree nodes |
| given the concrete syntax and<br>the actions and | the symbol classes<br>the abstract syntax can be generated |





# 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* |

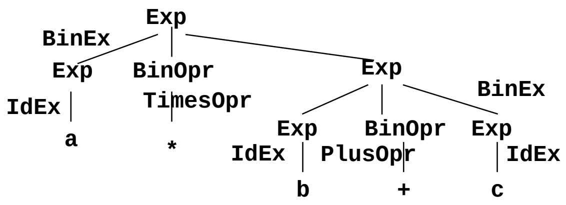



**derivation tree for `a * (b + c)`**

## 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





## Recursive descent parser

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

**Sytematic 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 pi | decision for branch pi |
| non-terminal occurrence X ::= ... Y ... | function call Y() |
| terminal occurrence X ::= ... t ... | accept a token t an read the next token |

**Example:**

```
p1: Stmt ::= Variable ':=' Expr  p2: Stmt ::= 'while' Expr 'do' Stmt
```

**Function:**

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

   default: Fehlerbehandlung();
}  }
```





## Grammar conditions for recursive descent

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

| | | | | |
|---|---|---|---|---|
| productions: | A ::= u | | A ::= v | |
| decision sets: | First (u Follow(A)) | $\cap$ | First (v Follow(A)) | $= \emptyset$ |

**First set** and **follow set:**

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

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) $\}$

**Example:**

| **production** | | | **decision set** |
|---|---|---|---|
| p1: | Prog | ::= Block # | begin |
| p2: | Block | ::= begin Decls Stmts end | begin |
| p3: | Decls | ::= Decl ; Decls | new |
| p4: | Decls | ::= | Ident begin |
| p5: | Decls | ::= 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 | ε new | Ident begin |
| Decl | new | ; |
| Stmts | begin Ident | ; end |
| Stmt | begin Ident | ; end |





## Grammar transformations for LL(1)

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

- **alternative productions that begin with the same symbols**
- **productions that are directly or indirectly left-recursive.**

Simple grammar transformations that keep the defined language invariant:

| | non-LL(1) productions | transformed |
|---|---|---|
| • **left-factorization:** $u, v, w \in V^*$; $X \in N$ does not occur in the original grammar | A ::= v u<br>A ::= v w | A ::= v X<br>X ::= u<br>X ::= w |
| • **elimination of direct recursion :** | A ::= A u<br>A ::= v | A ::= v X<br>X ::= u X<br>X ::= |

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

| | |
|---|---|
| for example repetition of u: | A ::= v ( u )* w |
| additional condition: | First(u) $\cap$ First(w Follow(A)) $= \emptyset$ |
| branch in the function body: | v **while (CurrToken in First(u)) { u }** w |

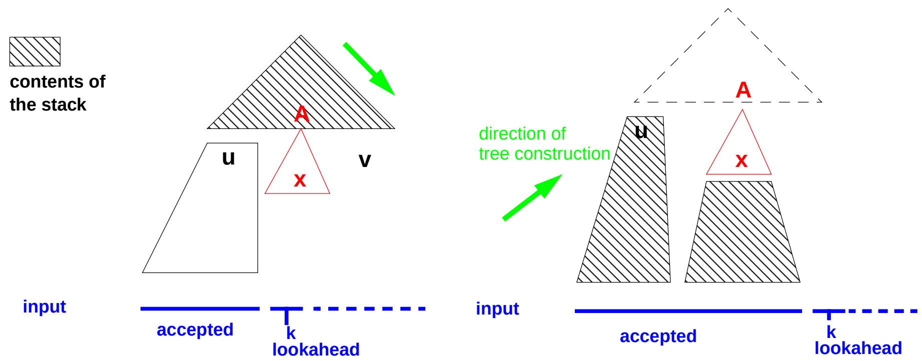
correspondingly for EBNF constructs $u^+$, [u]

## Comparison: top-down vs. bottom-up

Information a stack automata 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**.





## LR(1) automata

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).**

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** (also called situations):

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

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

**.** position of analysis

**R** expected **right context,** i. e. a set of terminals which may follow after the application of the complete production.
(for general k: R contains terminal sequences not longer than k)

**Reduce item:**

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

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

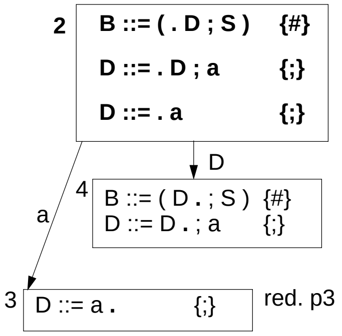
Each **state** of an automaton represents **LL: one item** **LR: a set of items**





## 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.

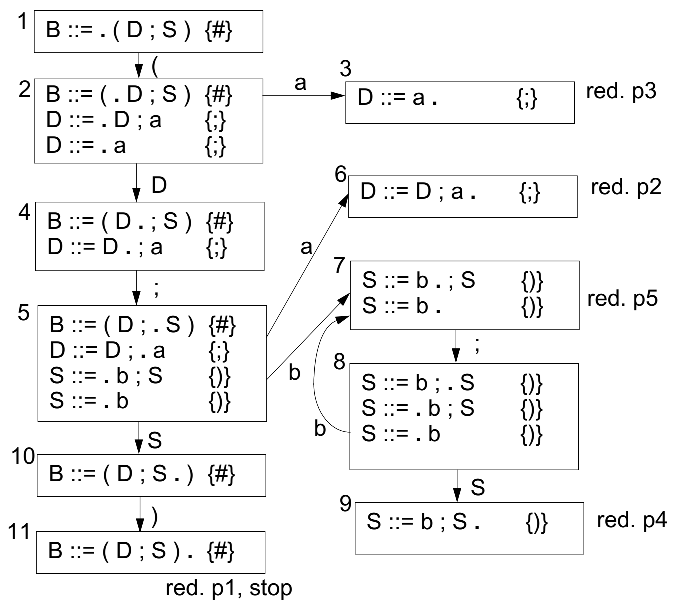
| | | |
|---|---|---|
| **Operations:** | **shift** | read and push the next state on the stack |
| | **reduce** | reduce with a certain production, pop n states from the stack |
| | **error** | error recognized, report it, recover |
| | **stop** | input accepted |





## 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



# Construction of LR(1) automata

Create the start state; create transitions and states as long as new ones can be created.

**Transitive closure** is to be applied to each state:
If **[ A ::= u . B v R ]** is in state q,
with the analysis position before a non-terminal B,
then for each production **B ::= w**
**[ B ::= . w First (v R) ]**
has to be added to state q.

*before:* 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 a corresponding item with the **analysis position advanced behind the x** occurrence.

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

D → 4 B ::= ( D . ; S ) {#}
D ::= D . ; a {;}

a → 3 D ::= a . {;}





# Operations of the LR(1) automaton

**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:**
recuce 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 | # | |





# 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**





# Shift-reduce conflict for „dangling else“ ambiguity

1
S ::= . Stmt {#}
Stmt ::= . if ... then Stmt {#}
Stmt ::= . if ... then Stmt else Stmt {#}
Stmt ::= . a {#}
Stmt →
a →

if ... then ↓

3
Stmt ::= if ... then . Stmt {#}
Stmt ::= if ... then . Stmt else Stmt {#}
Stmt ::= . if ... then Stmt {# else}
Stmt ::= . if ... then Stmt else Stmt {# else}
Stmt ::= . a {# else}
Stmt →
a →

if ... then ↓

5
Stmt ::= if ... then . Stmt {# else}
Stmt ::= if ... then . Stmt else Stmt {# else}
Stmt ::= . if ... then Stmt {# else}
Stmt ::= . if ... then Stmt else Stmt {# else}
Stmt ::= . a {# else}
if →
a →

Stmt ↓

6
Stmt ::= if ... then Stmt . {# else}
Stmt ::= if ... then Stmt . else Stmt {# else}
else →

shift-reduce conflict

# Simplified LR grammar classes

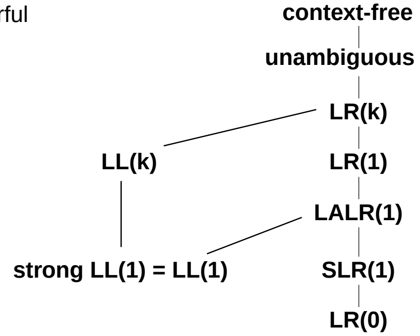
**LR(1):**
too many states for practical use
**Reason**: right-contexts distinguish many states
**Strategy:** simplify right-contexts sets,
fewer states, grammar classes are less powerful

**LR(0):**
all items **without right-context**
**Consequence:** reduce items only in
singleton sets

**SLR(1):**
**LR(0) states**; in reduce items
use larger right-context sets for decision:
**[ A ::= u . Follow (A) ]**

**LALR(1):**
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)**

**Grammar hierarchy:**
**(strict inclusions)**

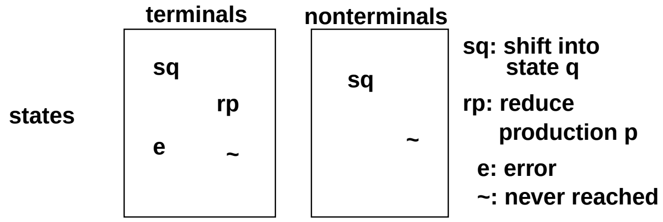







# Implementation of LR automata

**Table-driven:**




**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.





# Error handling: general criteria

- **recognize error as early as possible**
  LL and LR can do that
- **report the symptom in terms of the source text**
- **continue parsing short after the error position**
- **avoid avalanche errors**
- **build a tree that has a correct structure**
- **do not backtrack, do not undo actions**
- **no runtime penalty for correct programs**





# 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.

# Error recovery

**Continuation point**:
The 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*.

**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 id. e | **delete** `/ c` and **insert** error id. **e** |





# 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 of tokens as potential continuation points.

**Steps of the method:**

1. **Save the contents of the parse stack** when an error is recognized. Skip the error token.
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 influence on the computation of D.





# 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





# Design of concrete grammars

**Objectives**

The concrete grammars 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 provable related to the **documented grammar**;
- can be **mapped to** a suitable **abstract grammar**.

# 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 any modification**.
  (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`**





# Grammar design together with language design

**Read grammars** before writing a new grammar.

Apply **grammar patterns systematically** (cf. GdP-2.5, GdP-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





# 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 unreasonable complex**:
  e. g. distinction of compile-time expressions from ordinary expressions requires duplication of the expression syntax.





# Reasons of LALR(1) conflicts

| | Grammar condition does not hold: | |
|---|---|---|
| **context-free** | | |
| **unambiguous** | **ambiguous** | most cases |
| **LR(k)** | **unbounded lookahead** needed | |
| **LR(1)** | **fixed length lookahead > 1** needed | |
| **LALR(1)** | **merge of LR(1) states** introduces **conflicts** | rare cases |

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

## 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





## 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.





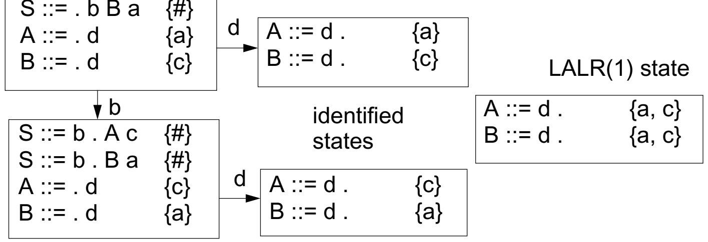
## LR(1) but not LALR(1)

**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.

LR(1) states




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





## 4. Semantic analysis and transformation

**Input:** **abstract program tree**

| **Tasks:** | **Compiler module:** |
|---|---|
| name analysis | environment module |
| properties of program entities | definition module |
| type analysis, operator identification | signature module |
| transformation | tree generator |

**Output:** **target tree, intermediate code, target program in case of source-to-source**

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:** tree walking algorithm that calls operations
in specified contexts and in an admissable order

# 4.1 Attribute grammars

Attribute grammar (AG) specifies **dependent computations in the abstract program tree declarative**: explicit dependencies only; a suitable order of execution is computed

Computations solve the tasks of semantic analysis and transformation

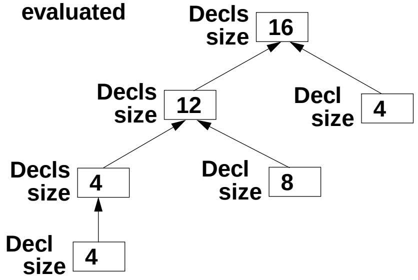
**Generator** produces **a plan for tree walks**
that execute calls of the computations,
such that the specified dependencies are obeyed,
computed values are propagated through the tree

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

**Example: attribute grammar**

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 = ...;**
END;

**tree with dependent attributes evaluated**








# Basic concepts of attribute grammars

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

```
RULE p: Y ::= u COMPUTE f(...); g(...); END;
```

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

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

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

post-condition (X.b = f(Y.a)), pre-condition (Y.a = g(...))

`f(Y.a)` uses the result of `g(...)`; hence `Y.a=g(...)` will be executed before `f(Y.a)`

**dependent computations in adjacent contexts:**

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

**attributes may specify dependencies without propagating any value:**

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

`ResetTypeOf` will be called before `GetTypeOf`





# Definition of attribute grammars

An **attribute grammar** is defined by

a **context-free grammar G**, (abstract syntax, tree grammar)

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: X ::= ... Y ... has exactly one computation
for all attributes of AS(X), and
for all attributes of AI(Y), for all symbol occurrences on the right-hand side of p





# AG Example: Compute expression values

The AG specifies: The value of an expression is computed and printed:

```
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;
```

## AG Binary numbers

**Attributes:**

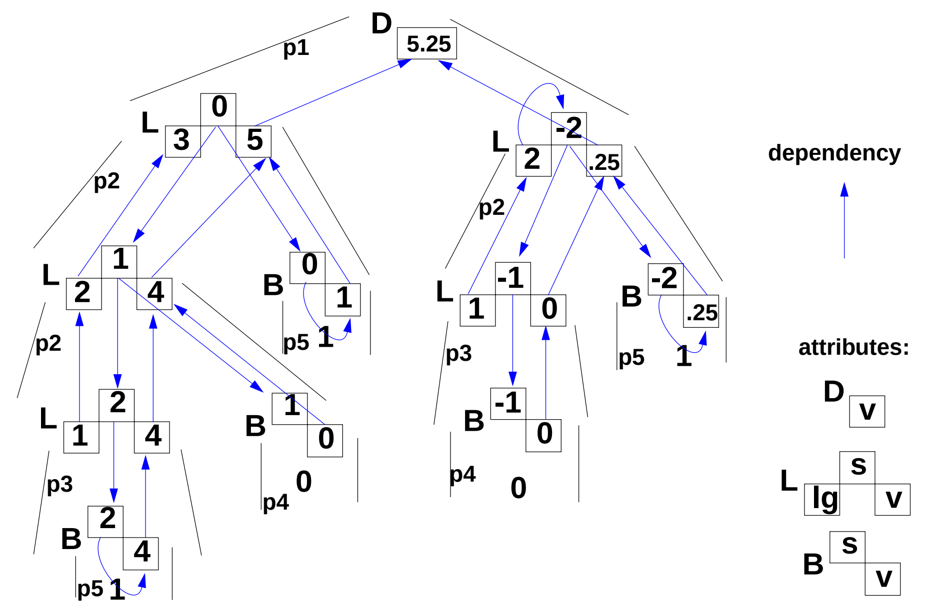
| | | |
|---|---|---|
| | `L.v, B.v` | value |
| | `L.lg` | number of digits in the sequence L |
| | `L.s, B.s` | scaling of B or the least significant digit of L |

```
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;
```





## An attributed tree for AG Binary numbers





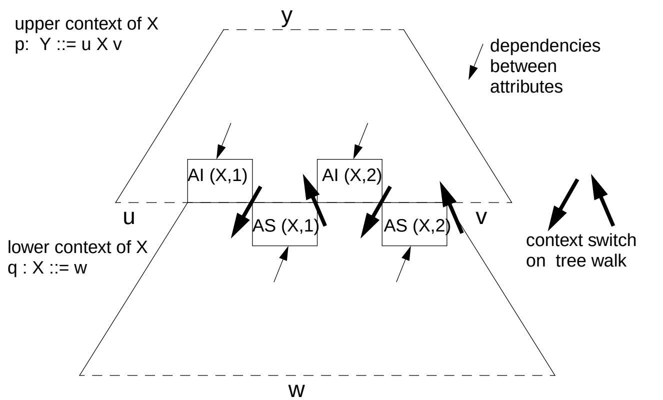



## Dependency analysis for AGs

**2 disjoint sets of attributes for each symbol X:**

**AI (X) : inherited** (dt. erworben), **computed in upper contexts** of X

**AS (X): synthesized** (dt. abgeleitet), **computed in lower contexts** of X.




**Objective: Partition** of attribute sets, such that

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

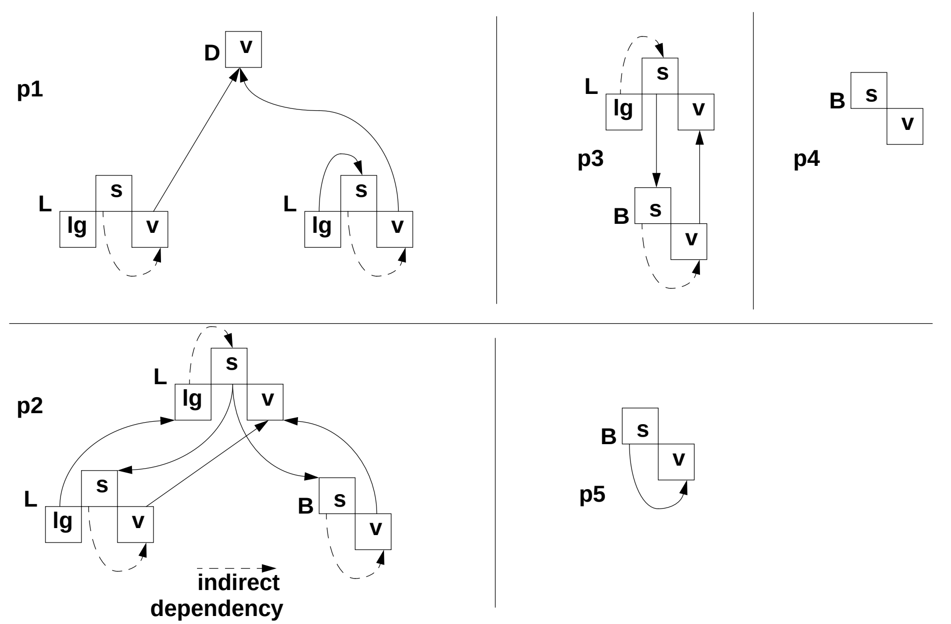
**AS (X, i)** is computed **during the i-th visit** of X

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





## Dependency graphs for AG Binary numbers



# 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** when visiting a context for which they are specified.
- The execution order obeys the **attribute dependencies**.

| **Pass-oriented strategies** for the tree walk: | **AG class** |
|---|---|
| k times **depth-first left-to-right** | **LAG (k)** |
| k times depth-first **alternatingly left-to-right / right-to left** | **AAG (k)** |
| once **bottom-up** | **SAG** |

The attribute dependencies of the AG are checked
whether the desired pass-oriented strategy is applicable; see LAG(k) algorithm.

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

Generator fits the plans to the dependencies.





# Visit-sequences

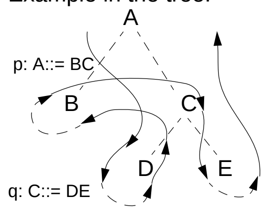
A **visit-sequence** (dt. Besuchssequenz) $vs_p$ **for each production** of the tree grammar:

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

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

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

Example in the tree:

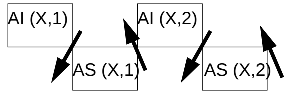



visit-sequences

$vs_p$: ... ↓C,1 ...↓B,1 ...↓C,2 ...↑1

$vs_q$: ... ↓D,1 ... ↑1 ... ↓E,1 ... ↑2

**attribute partitions**
guaranty
correct interleaving:




**Implementation:**

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





# 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'**

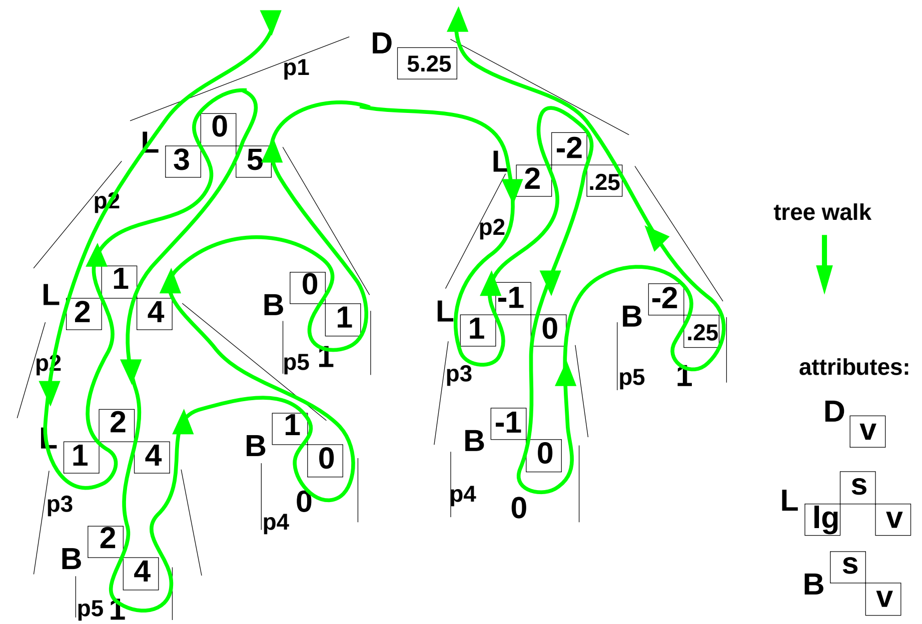
**B.v=Power2(B.s); ↑1**

**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





# Tree walk for AG Binary numbers

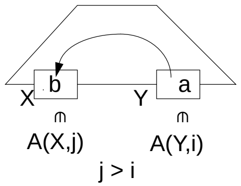


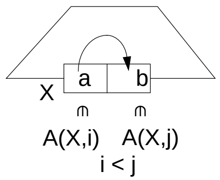
# LAG (k) condition and algorithm

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.

Necessary and sufficient condition over dependency graphs - expressed graphically:

A dependency **from right to left**




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

**Algorithm:** computes A (1), ..., A (k), if the AG is LAG(k), for i = 1, 2, ...

A (i) := all attributes that are not yet assigned

remove attributes from A(i) as long as the following rules are applicable:

- remove X.b, if there is a context where it depends on an attribute of A (i) according to the pattern given above,
- remove Z.c, if it depends on a removed attribute

**Finally**: all attributes are assigned to a passes i = 1, ..., k the AG **is LAG(k)**
all attributes are removed from A(i) the AG **is not LAG(k) for any k**





# Generators for attribute grammars

| | | |
|---|---|---|
| **LIGA** | University of Paderborn | OAG |
| **FNC-2** | INRIA | ANCAG (Oberklasse von OAG) |
| **Synthesizer Generator** | Cornell University | OAG, inkrementell |
| **CoCo** | Universität Linz | LAG(1) |

**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**



# State attributes without values

```
RULE: Root ::= Expr COMPUTE
  Expr.print = "yes";
  printf ("\n") <- Expr.printed;
END;
RULE: Expr ::= Number COMPUTE
  Expr.printed =
    printf ("%d ", Number) <- Expr.print;
END;
RULE: Opr  ::= '+' COMPUTE
  Opr.printed = printf ("+ ") <- Opr.print;
END;
RULE: Opr  ::= '*' COMPUTE
  Opr.printed = printf ("* ") <- Opr.print;
END;
RULE: Expr  ::= Expr Opr Expr COMPUTE
  Expr[2].print = Expr[1].print;
  Expr[3].print = Expr[2].printed;
  Opr.print = Expr[3].printed;
  Expr[1].printed = Opr.printed;
END;
```

The attributes `print` and `printed` do not have a value

They just describe pre- and post-conditions of computations:

`Expr.print:`
postfix output has been done up to not including this node

`Expr.printed:`
postfix output has been done up to including this node





# Dependency pattern CHAIN

```
CHAIN print: VOID;
RULE: Root ::= Expr COMPUTE
  CHAINSTART HEAD.print = "yes";
  printf ("\n ") <- TAIL.print;
END;
RULE: Expr ::= Number COMPUTE
  Expr.print =
    printf ("%d ", Number) <- Expr.print;
END;
RULE: Opr ::= '+' COMPUTE
  Opr.post = printf ("+") <- Opr.pre;
END;
RULE: Expr ::= Expr Opr Expr COMPUTE
  Opr.pre = Expr[3].print;
  Expr[1].print = Opr.post;
END;
```

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

**Trivial computations** of the form X.a = Y.b in the CHAIN order can be **omitted**. They are added as needed.

## 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;
TERM Ident: int;
RULE: Definition ::= ‘define' Ident  COMPUTE
  printf ("%s defined on depth %d\n ",
           StringTable (Ident),
           INCLUDING Block.depth);
END;
```

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

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

**Propagation** through the contexts in between is **omitted**.





## Dependency pattern CONSTITUENTS

```
RULE: Block ::= '{' Sequence '}' COMPUTE
  Block.DefDone =
    CONSTITUENTS Definition.DefDone;
END;
RULE: Definition ::= 'Define' Ident COMPUTE
  Definition.DefDone =
    printf ("%s defined in line %d\n",
            StringTable(Ident), LINE);
END;
RULE: Usage ::= 'use' Ident COMPUTE
   printf ("%s used in line %d\n ",
           StringTable(Ident), LINE),
   <- INCLUDING BLOCK.DefDone;
END;
```

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

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

**Propagation** through the contexts in between is **omitted**.

The shown combination with INCLUDING is a common dependency pattern.





## 4.2 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 the 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;<br>yields the default-Wert d, if P has not been set |

**Operations are called as dependent computations in the tree**

**Implementation:** a property list for every key, for example

**Generation of the definition module**: From specifications of the form

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

functions ResetElementNumber, SetElementNumber, GetElementNumber are generated.



## 4.3 Type analysis

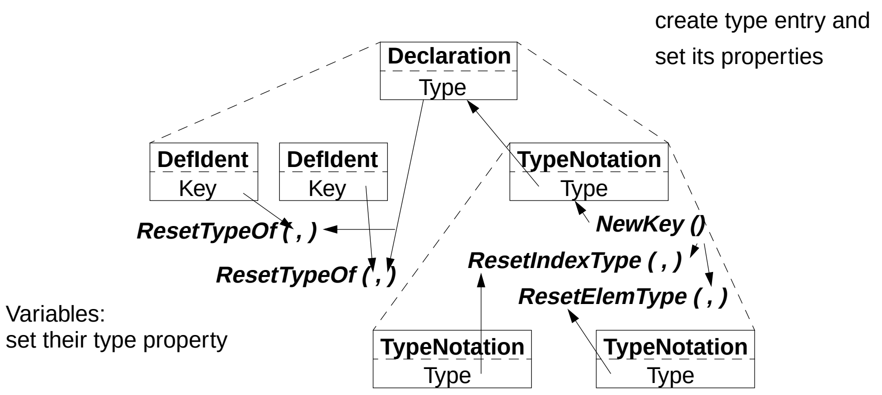
**Task: Compute and check types of program entities and constructs at compile time**

- **defined entities** (e. g. variables)
  **have a type property**, stored in the definition module
- **program constructs** (e. g. expressions)
  **have a type attribute,** associated to their symbol resp. tree node
  special task: **resolution of overloaded operators** (functions, methods)
- **types themselves are program entities**
  represented by keys;
  **named** using type definitions; **unnamed** in complex type notations
- **types have properties**
  e. g. the element type of an array type
- **type checking for program entities and for program constructs**
  a type must / may not have certain properties in certain contexts
  compare expected and given type; **type relations**: equal, compatible;
  compute type **coercion**

# Declarations and type notations

operations in the tree for the construct:

```
a, b: array [1..10] of real;
```

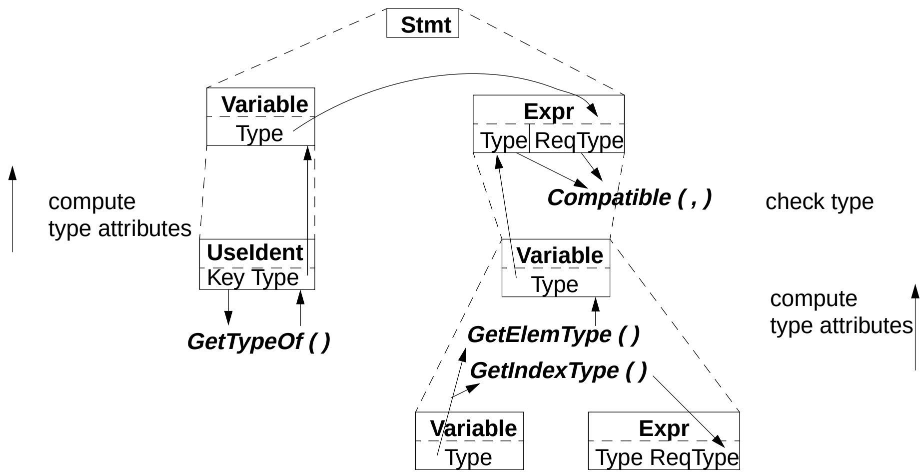





# Types of expressions required by context

operations in the tree for:

```
x := a[i];
```





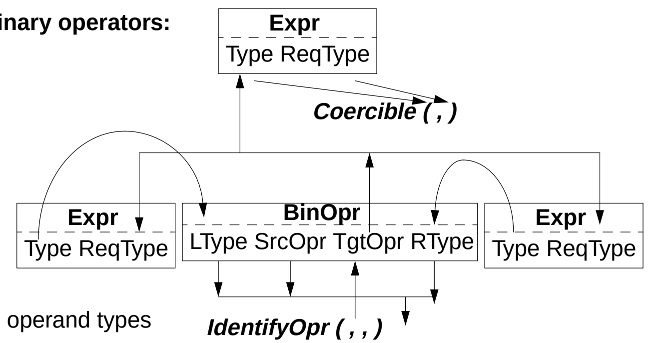

# Overloading resolution for operators

**Overloading**: **same operator symbol** (source operator) is used for **several target operators** having **different signatures** and **different meanings**, e. g. specified by a table like:

| **symbol** | **signature** | **meaning** |
|---|---|---|
| + | int X int -> int | addition of integral numbers |
| + | real X real -> real | floating point addition |
| + | set X set -> set | union of sets |
| = | t X t -> boolean | comparison for values of type t |

**Coercion:** implicitly applicable type conversion: e. g. int -> real, char -> string, ...

**Context of overloaded binary operators:**




given: source operator and operand types
find: target operator



# Type analysis for object-oriented languages

**Class hierarchy is a type hierarchy:**

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

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

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

**Check signature of overriding methods:**

calls must be type safe; Java requires the same signature;
following weaker requirements are 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; } }`

**Analyse dynamic methode binding; try to decide it statically:**

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

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

# 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;
```

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

```
'c  = bool
'b  = 'a
'd  = 'a
'a  = int
```

solve the system of equations:

```
choice: (int * (int->bool)) -> int
```





# 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)
```





# 4.4 Name analysis

Identifiers identify program entities in the program text (**statically**).

The **definition** of an identifier b introduces a **program entity** and **binds** it to the **identifier**.
The binding is valid in a certain range of the program text: the **scope of the definition**.

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

**Hiding rules** for languages with nested structures:

- **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. Algol 60, Pascal, Java, ... with additional rules)
- **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. (e. g. C, C++, Java, ... with additional rules)

**Ranges** are syntactic constructs like **blocks, functions, modules, classes, packets**
- as defined for the particular language.

**Implementation** of name analysis:
Operations of the environment module are called in suitable tree contexts.





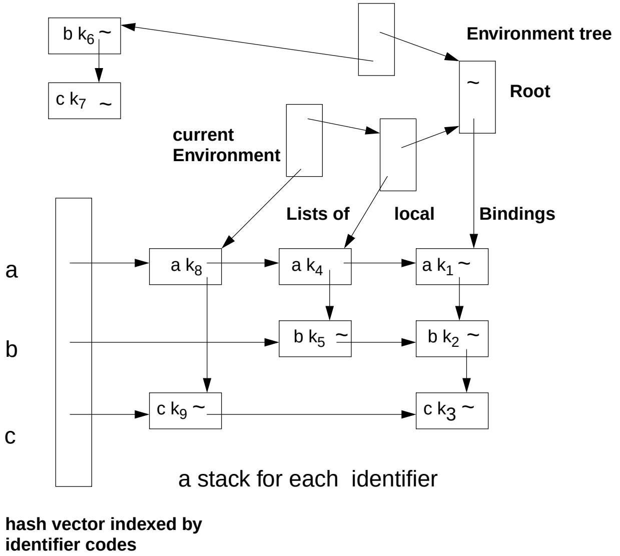
# Environment module

Implements the abstract data type **Environment**:
hierarchically nested sets of **Binding**s **(identifier, environment, key)**

**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. |

## Data structure of the environment module




$k_i$: key of the defined entity



## Environment operations in tree contexts

Operations in tree contexts and the order they are called 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).





## Semantic error handling

**Design rules:**

Error reports **related to the source code**:

- any explicit or implicit **requirement of the language definitions** needs to be checked by an operation in the tree
- check has to be associated to the **smallest relevant context** yields precise source position for the report; propagate information to that context if necessary
- **meaningfull error report**
- **different reports for different violations**, do not connect texts 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`**





## 5. Transformation

Create **target tree** to represent the program in the intermediate language.

**Intermediate language** spcified externally or designed for the abstract source machine.

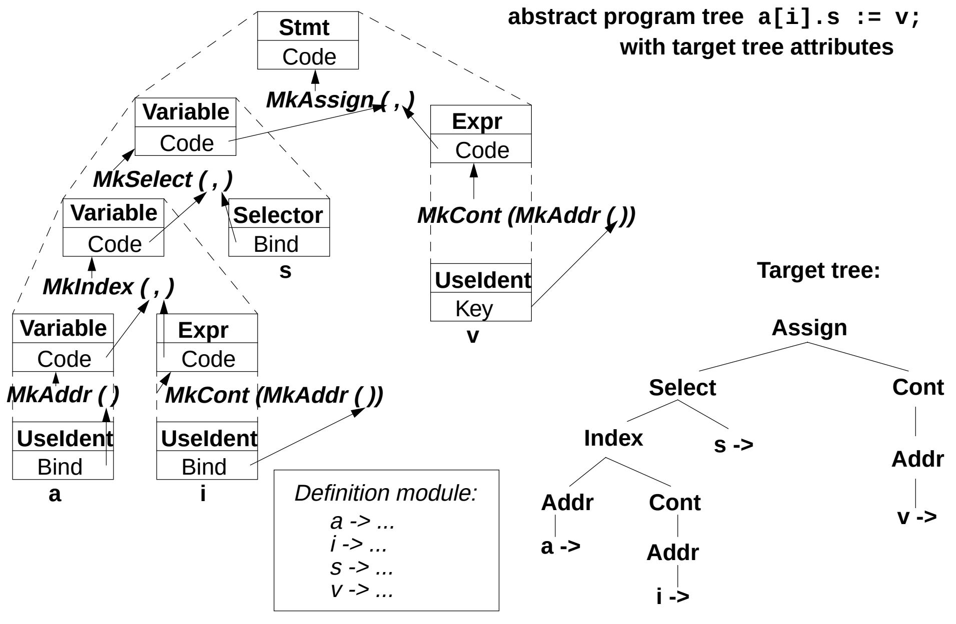
**Design rules**:

- **simplify the structure**
  only those constructs and properties that are needed for the synthesis phase;
  omit declarations and type denotations - they are kept in the definition module
- **unify constructs**
  e. g. standard representation of loops, or translation into jumps and labels
- **distinguished target operators for overloaded operators**
- **explicit target operators for implicit source operations**
  e. g. type coercion, contents operation for variable access, run-time checks

Transfer **target tree and definition module to synthesis phase**
as data structure, file, or sequence of function calls

For **source-to-source translation** the target tree represents the **target program**.
The target text is produced from the tree by **recursive application of text patterns**.

# Example: Target tree construction






# Attribute grammar for target tree construction (CI-93)

**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;**



# 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);`





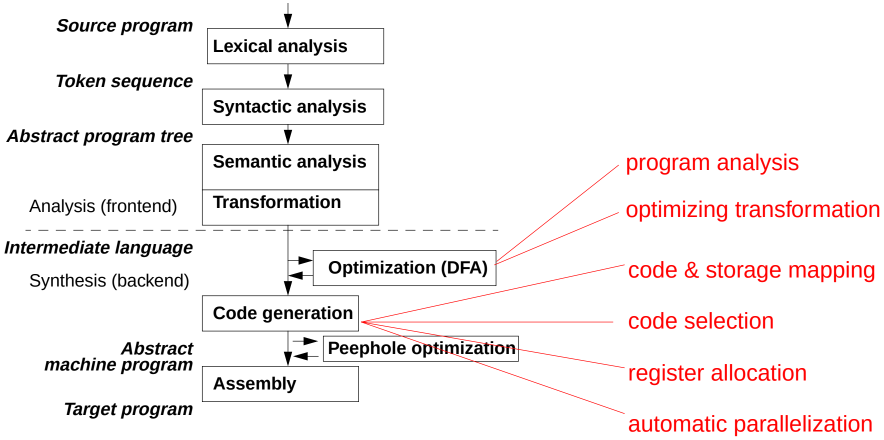
# PTG Patterns for creation of HTML-Texts

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> <A HREF="#position_Train">Train</A>
</UL>
```

# 6. Synthesis: An Overview








# Optimization

**Objective**: Reduce run-time and/or code size of the program, without changing its effect.
Eliminate redundant computations, simplify computations.

| | |
|---|---|
| **Input:** | Program in intermediate language |
| **Task:** | **Analysis** (find redundancies), apply **transformations** |
| **Output:** | Improved program in intermediate language |

**Program analysis:**
**static properties** of program structure and execution
**safe, pessimistic assumptions** where input and dynamic execution paths are not known

**Context of analysis:**

| | | |
|---|---|---|
| Expression | local optimization | |
| Basic block | local optimization | |
| Control flow graph (procedure) | global | intra-procedural optimization |
| Control flow graph, call graph | global | inter-procedural optimization |





# Optimizing Transformations

| Name of transformation: | Example for its application: |
|---|---|
| • Algebraic simplification of expressions | `2*3.14  x+0   x*2  x**2` |
| • Constant propagation (dt. Konstantenweitergabe) | `x = 2; ... y = x * 5;` |
| • Common subexpressions (Gemeinsame Teilausdrücke) | `x=a*(b+c);...y=(b+c)/2;` |
| • Dead variables (Überflüssige Zuweisungen) | `x = a + b; ... x = 5;` |
| • Copy propagation (Überflüssige Kopieranweisungen) | `x = y; ... ; z = x;` |
| • Dead code (nicht erreichbarer Code) | `b = true;...if (b) x = 5; else y = 7;` |
| • Code motion (Code-Verschiebung) | `if (c) x = (a+b)*2; else x = (a+b)/2;` |
| • Function inlining (Einsetzen von Aufrufen) | `int Sqr (int i) { return i * i; }` |
| • Loop invariant code | `while (b) {... x = 5; ...}` |
| • Induction variables in loops | `i = 1; while (b) { k = i*3; f(k); i = i+1;}` |

Analysis checks **preconditions for safe application** of each transformation;
**more applications,** if preconditions are analysed in **larger contexts**.

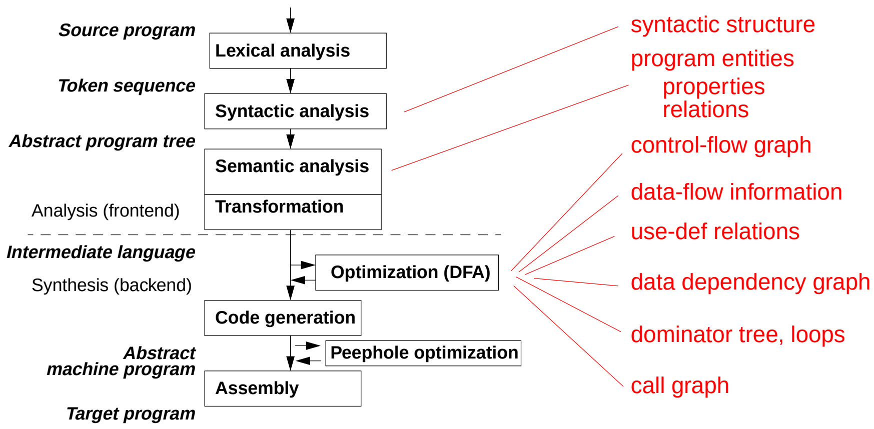
**Interdependences:**
Application of a transformation may **enable or inhibit** another application of a transformation.

**Order of transformations** is relevant.





# Analysis in Compilers

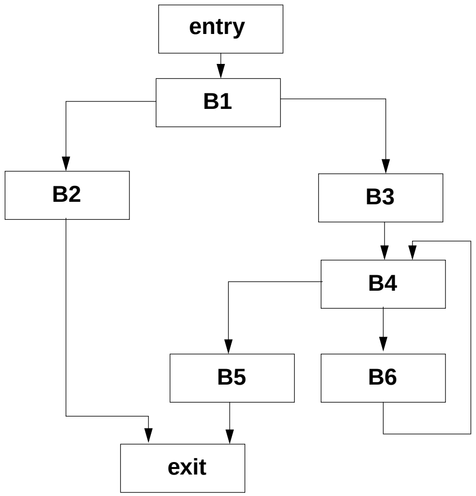


## Example for a Control-flow Graph

Intermediate code with basic blocks:

| | |
|---|---|
| `receive m`<br>`f0 <- 0`<br>`f1 <- 1`<br>`if m <= 1 goto L3` | B1 |
| `i <- 2` | B3 |
| `L1: if i <= m goto L2` | B4 |
| `return f2` | B5 |
| `L2: f2 <- f0 + f1`<br>`f0 <- f1`<br>`f1 <- f2`<br>`i <- i + 1`<br>`goto L1` | B6 |
| `L3: return m` | B2 |

Control-flow graph:
*[Muchnick, p. 172]*








## Data-Flow Analysis

Data-flow analysis (DFA) provides information about how the execution of a program may manipulate its data.

Many different problems can be formulated as **data-flow problems**, for example:

- Which assignments to variable **v** may influence a use of **v** at a certain program position?
- Is a variable **v** used on any path from a program position **p** to the exit node?
- The values of which expressions are available at program position **p**?

Data-flow problems are stated in terms of

- **paths through the control-flow graph** and
- **properties of basic blocks**.

Data-flow analysis provides information for **global optimization.**

Data-flow analysis does **not** know

- input values provided at run-time,
- branches taken at run-time.

Its results are to be interpreted **pessimistic**.





## Specification of a DFA Problem

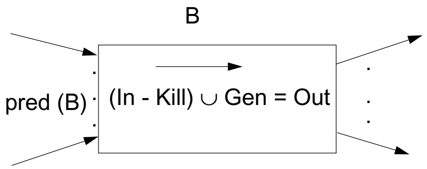
Specification of reaching definitions:

- **Description**:
  A definiton **d** of a variable **v** reaches the begin of a block **B**
  if **there is a path** from **d** to **B** on which **v** is not assigned again.
- It is a **forward problem**.
- The **meet operator** is union.
- The **analysis information** in the sets are assignments at certain program positions.
- **Gen (B)**:
  contains all definitions **`d: v = e;`** in **B**,
  such that **v** is not defined after **d** in **B**.
- **Kill (B)**:
  if v is assigned in B, then Kill(B)
  contains all definitions **`d: v = e;`**
  in blocks different from **B**,
  such that **B** has a definition of **v**.

**2 equations for each basic block:**

$$Out(B) = Gen(B) \cup (In(B) - Kill(B))$$

$$In(B) = \underset{h \in pred(B)}{\Theta} Out(h)$$





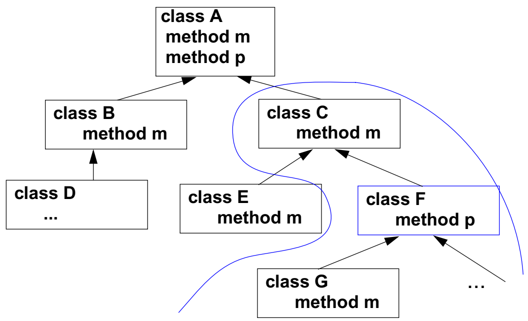



## Call Graphs for object-oriented programs

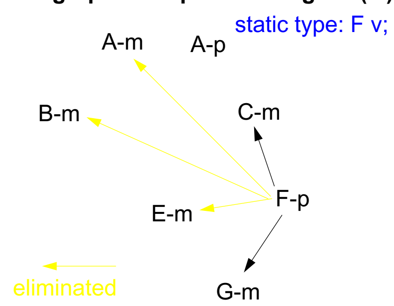
The call graph is reduced to a set of **reachable methods** using the **class hierarchy** and the **static type of the receiver** expression in the call:

If a method F-p **is reachable** and
if it contains a **dynamically bound call v.m(...)** and
**T is the static type of v**,

then every method **m that is inherited by T or by a subtype of T is also reachable**, and arcs go from F-p to them.




**Call graph for F-p containing v.m(...)**



# Code Generation

**Input:** Program in intermediate language

**Tasks:**

| | |
|---|---|
| Storage mapping | properties of program objects (size, address) in the definition module |
| Code selection | generate instruction sequence, optimizing selection |
| Register allocation | use of registers for intermediate results and for variables |

**Output:** abstract machine program, stored in a data structure

**Design of code generation:**

- analyze **properties of the target processor**
- plan **storage mapping**
- design at least one **instruction sequence** for each operation of the intermediate language

**Implementation of code generation:**

- Storage mapping:
  a traversal through the program and the definition module computes
  sizes and addresses of storage objects
- Code selection: use a generator for pattern matching in trees
- Register allocation:
  methods for expression trees, basic blocks, and for CFGs





# Storage Mapping

**Objective:**
for each storable program object compute storage class, relative address, size

**Implementation:**
use properties in the definition module, travers defined program objects

**Design the use of storage areas:**

| | |
|---|---|
| code storage | progam code |
| global data | to be linked for all compilation units |
| run-time stack | activation records for function calls |
| heap | storage for dynamically allocated objects, garbage collection |
| registers for | addressing of storage areas (e. g. stack pointer)<br>function results, arguments<br>local variables, intermediate results (**register allocation**) |

**Design the type mapping ... C-29**

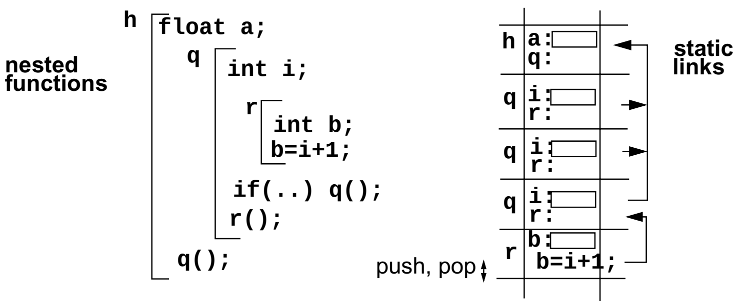




# Run-Time Stack

**Run-time stack** contains one **activation record** for each active function call.
Activation record provides storage local data of a function call. (see C-31)

**Nested functions** (nested classes and objects): static predecessor chain
links the accessible activation records, **closure of a function**




Requirement: The closure of a function is still on the run-time stack when the function is called.

Languages without recursive functions (FORTRAN) do not use a run-time stack.

Optimization: activation records of **non-recursive functions** may be allocated statically.

Parallel processes, threads, coroutines need a **separate run-time stack** each.





# Code Sequences for Control Statements

A **code sequence** defines how a **control statement** is transformed into jumps and labels.

Several variants of code sequences may be defined for one statement.

Example:

```
while (Condition) Body       M1:  Code (Condition, false, M2)
                                  Code (Body)
                                  goto M1
                             M2:
```

variant:

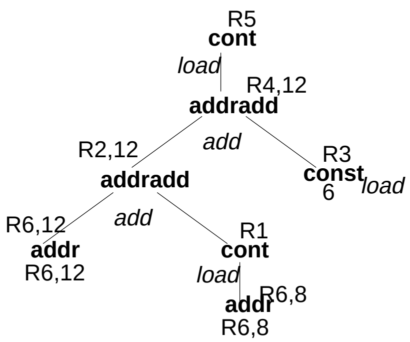
```
                                  goto M2
                             M1:  Code (Body)
                             M2:  Code (Condition, true, M1)
```

Meaning of the **`Code`** constructs:

| | |
|---|---|
| `Code (S):` | generate code for statements **`S`** |
| `Code (C, true, M)` | generate code for condition **`C`** such that<br>it branches to M if **`C`** is true,<br>otherwise control continues without branching |

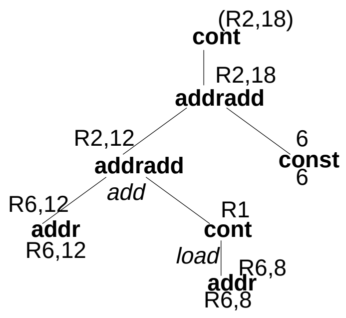
# Example for Code Selection

tree for assignment ... = **a[i].s;**




*load (R6,8), R1*
*add R6,R1,R2*
*load 6,R3*
*add R2,R3,R4*
*load (R4,12),R5*
*store R5, ...*

cost: 6 instructions




*load (R6,8), R1*
*add R6,R1,R2*
*store (R2,18),...*

cost: 3 instructions





# Register Allocation

**Use of registers:**

intermediate results of expression evaluation

reused results of expression evaluation (CSE)

contents of frequently used variables

parameters of functions, function result (cf. register windowing)

stack pointer, frame pointer, heap pointer, ...

Number of registers is limited - for each register class: address, integer, floting point

**register allocation aims at ruduction of**

- number of memory accesses
- spill code, i. e. instructions that store and reload the contents of registers

**specific allocation methods for different context ranges:**

- expression trees (Sethi, Ullman)
- basic blocks (Belady)
- control flow graphs (graph coloring)

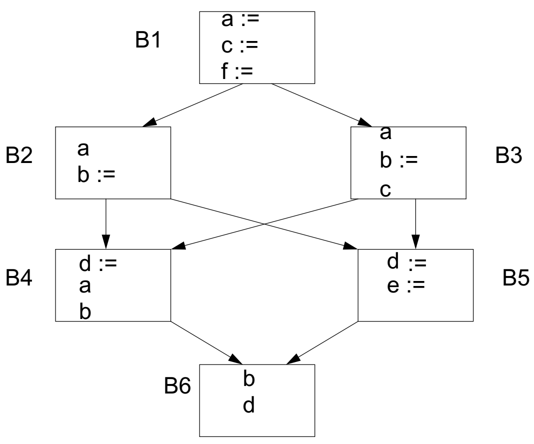
**useful technique:** defer register allocation until a later phase, use an unbound set of **symbolic registers** instead



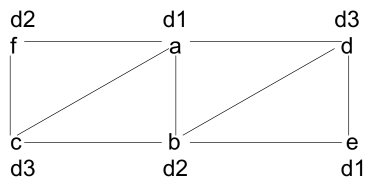


# Example for Graph Coloring

**CFG with definitions and uses of variables**




**interference graph**





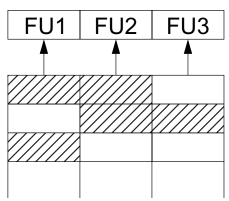



# Code Parallelization

Target processor executes several instructions in parallel.
Compiler arranges instruction sequence for shortest execution time: **instruction scheduling**

Principles of parallelism in processors:

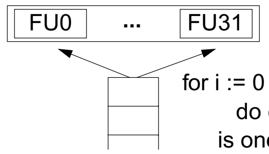
**Parallel functional units (FU)**
**super scalar, VLIW:**




parallelized instruction sequence

**Data parallel processor**
**vector processor**

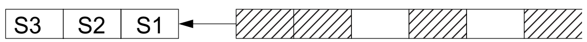
all FUs execute the same instruction on individual data (SIMD)




for i := 0 to 31
do c[i] := a[i] + b [i];
is one instruction!

Analyze and transform loops

**Pipeline processor**




sequential code scheduled for pipelining

# Software Pipelining

Technique for parallelization of loops.

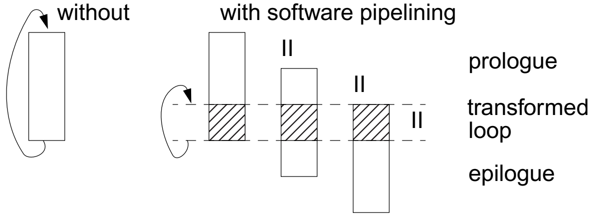
A single loop body does not exhibit enough parallelism => sparse schedule.

Idea of software pipelining:
transformed loop body executes several loop iterations in parallel,
iterations are shifted in time => compact schedule

Prologue, epilogue: initiation and finalization code

**Technique**:

1. **DDG** for loop body with dependencies into later iterations
2. Find a schedule such that iterations can begin with a **short initiation interval II**
3. Construct new loop, prologue, and epilogue




II: Initiation Interval





# Loop Parallelization

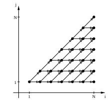
Compilation steps:

- **nested loops** operating on **arrays**, sequentiell execution of iteration space

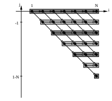
```
DECLARE B[0..N,0..N+1]

FOR I := 1 ..N
    FOR J := 1 .. I
        B[I,J] :=
            B[I-1,J]+B[I-1,J-1]
    END FOR
END FOR
```

- analyze **data dependencies**
  data-flow: definition and use of array elements



- **transform loops**
  keep data dependencies intact
- **parallelize inner loop(s)**
  map onto field or vector of processors



- **map arrays onto processors**
  such that many acceses are local,
  transform index spaces