# 3. Context-free Grammars and Syntactic Analysis

| | |
|---|---|
| **Input:** | **token sequence** |
| **Tasks:** | **Parsing**: construct a derivation according to the **concrete syntax**,<br>**Tree construction:** build a structure tree according to the **abstract syntax**,<br>**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 SS 2006 / 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

# 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 unambigous | is usually ambiguous |
| specifies derivation and parser | translation phase is based on it |
| parser actions specify the ---> | 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`** | |
| semantically relevant chain productions | are kept |
| **`ParameterDecl ::= Declaration`** | |
| terminal symbols | only semantically relevant ones are kept |
| identifiers, literals, | identifiers, literals |
| keywords, special symbols | |
| concrete syntax and symbol mapping specify | abstract syntax (can be generated) |

## Lecture Programming Languages and Compilers SS 2006 / 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

**Exercises:**

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

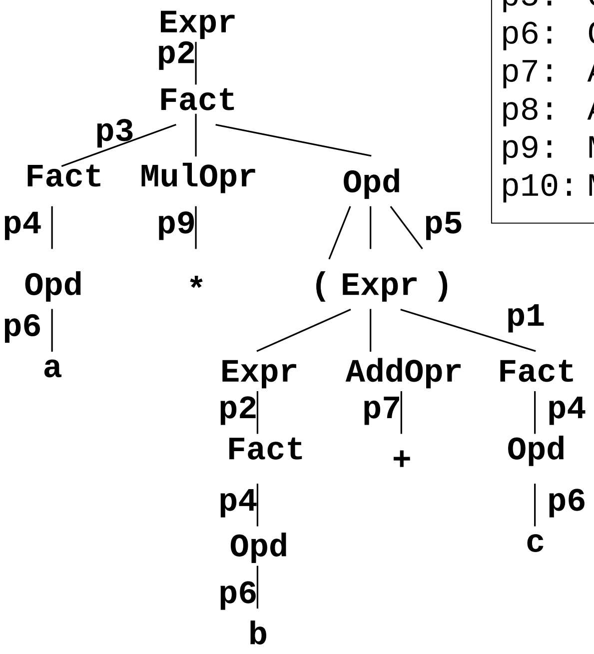
**Questions:**

- 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)`



## Lecture Programming Languages and Compilers SS 2006 / 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

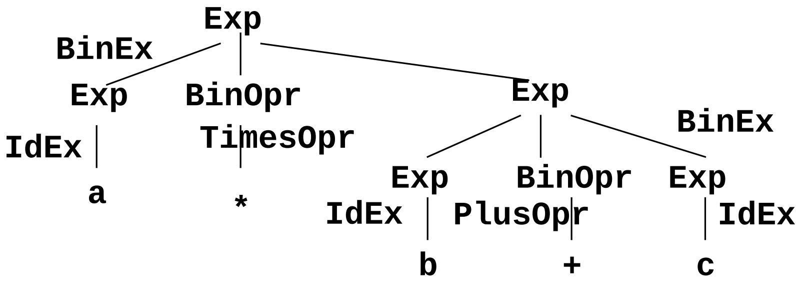
**Questions:**

- 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?

# 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

## Lecture Programming Languages and Compilers SS 2006 / Slide 304

**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 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 $p_i$ | 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();
}  }
```

## Lecture Programming Languages and Compilers SS 2006 / Slide 305

**Objectives:**

Understand the construction schema

**In the lecture:**

Explanation of the method:

- 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**, the **decision sets are disjoint**:

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

**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: | 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 | ε new | Ident begin |
| Decl | new | ; |
| Stmts | begin Ident | ; end |
| Stmt | begin Ident | ; end |

## Lecture Programming Languages and Compilers SS 2006 / Slide 306

**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?

# 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:**<br>$u, v, w \in V^*$<br>$X \in N$ 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: $\text{First}(u) \cap \text{First}(w\ \text{Follow}(A)) = \emptyset$
branch in the function body: v **while (CurrToken in First(u)) { u }** w
correspondingly for EBNF constructs $u^+$, [u]

## Lecture Programming Languages and Compilers SS 2006 / Slide 307

**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.
- Show EBNF productions in recursive descent parsers.

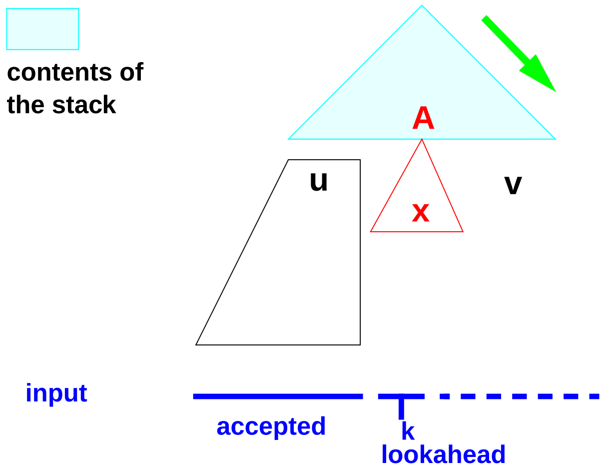
**Questions:**

- Apply recursion elimination for expression grammars.
- Write a strong LL(1) expression grammar using EBNF.

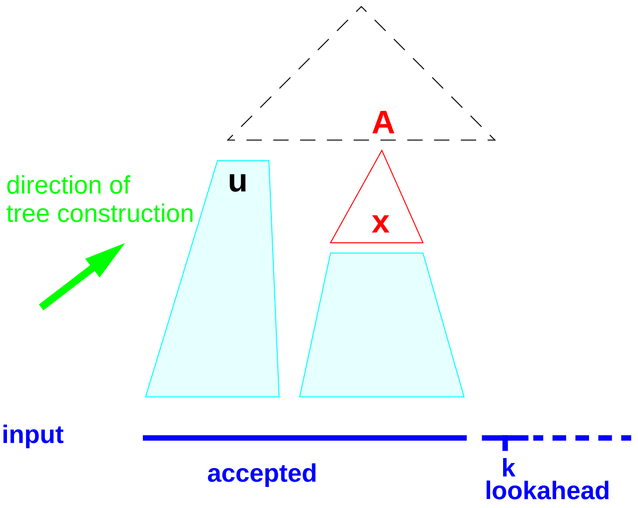
# Comparison: top-down vs. bottom-up

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**.

## Lecture Programming Languages and Compilers SS 2006 / Slide 308

**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

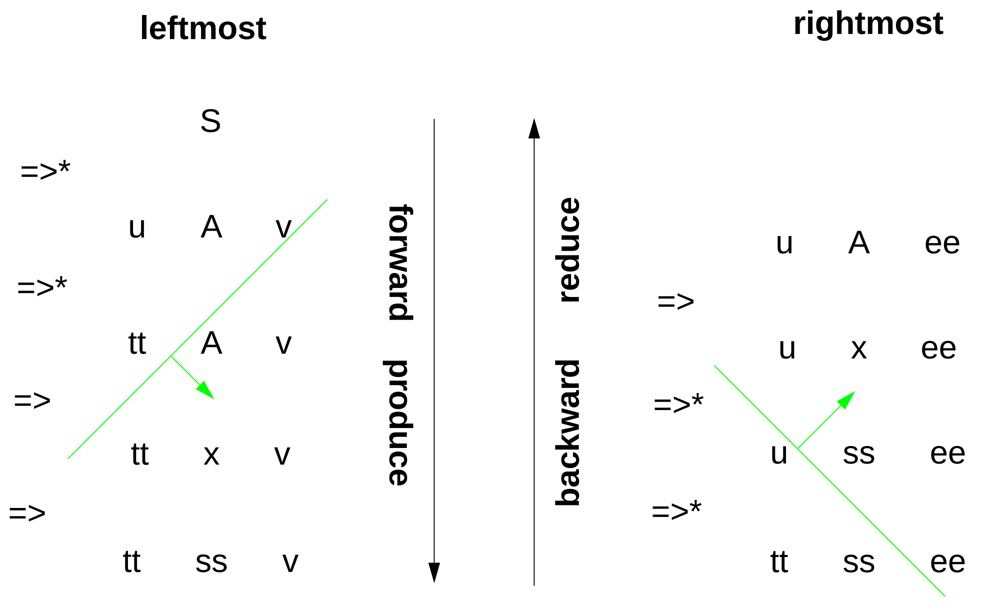
**Suggested reading:**

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.

# Leftmost and rightmost derivations



$u, v \in V^*$

$tt, ss, ee \in T^*$

$A \in N$

## Lecture Programming Languages and Compilers SS 2006 / Slide 309

**Objectives:**

Understand rightmost derivation backward

**In the lecture:**

- Explain the two derivation patterns.

# 3.3 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.

## Lecture Programming Languages and Compilers SS 2006 / Slide 310

**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 ) {#}]**

▪ 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.
(for general k>1: R contains sequences of terminals not longer than k)

**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 of reductions!

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

## Lecture Programming Languages and Compilers SS 2006 / Slide 311

**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:**

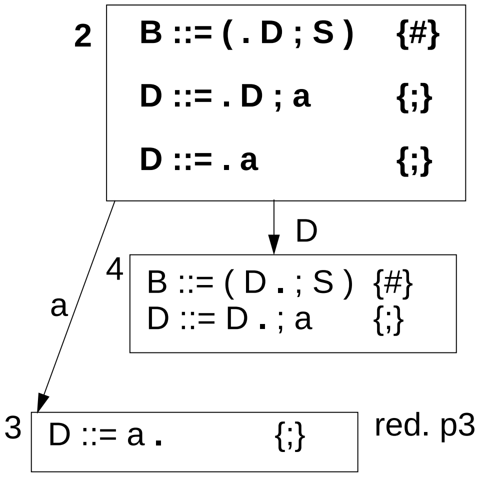
Kastens / Übersetzerbau, Section 4.3

**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 |

## Lecture Programming Languages and Compilers SS 2006 / Slide 312

**Objectives:**

Understand LR(1) states and operations

**In the lecture:**

Explain

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

**Suggested reading:**

Kastens / Übersetzerbau, Section 4.3

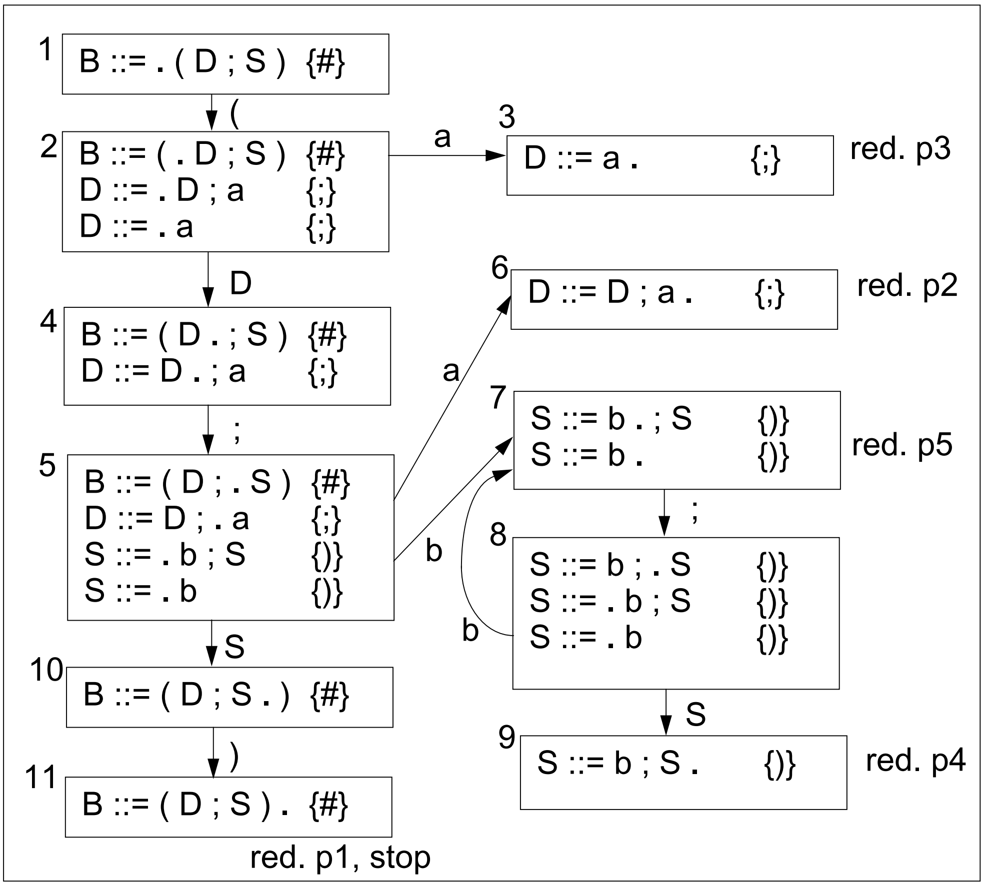
**Questions:**

- 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



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

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

3 D ::= a . {;} red. p3

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

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

6 D ::= D ; a . {;} red. p2

7 S ::= b . ; S {)}
S ::= b . {)} red. p5

8 S ::= b ; . S {)}
S ::= . b ; S {)}
S ::= . b {)}

9 S ::= b ; S . {)} red. p4

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

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

red. p1, stop

## Lecture Programming Languages and Compilers SS 2006 / Slide 313

**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. 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**:

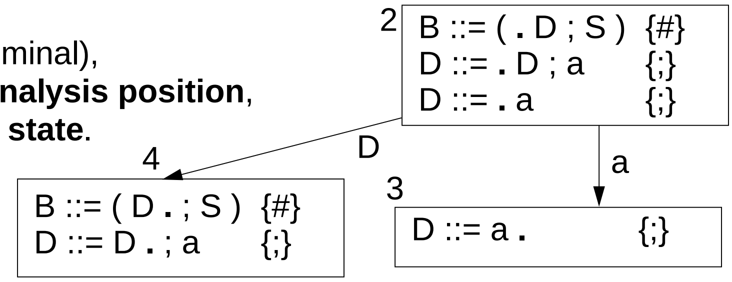
Closure of **[ S ::= . u {#} ]**
S ::= u is the **unique start production**,
# is an **artificial end symbol** (eof)

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 corresponding items
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 **.** {;}

## Lecture Programming Languages and Compilers SS 2006 / 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 | # | |

## Lecture Programming Languages and Compilers SS 2006 / Slide 315

**Objectives:**

Understand how the automaton works

**In the lecture:**

Explain operations

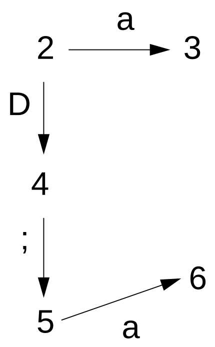
**Questions:**

- 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:

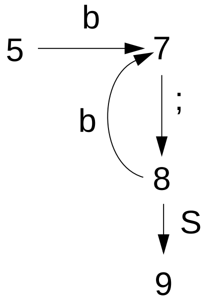
D ::= D ; a
D ::= a



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

**right recursive** productions:

S ::= b ; S
S ::= b



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

## Lecture Programming Languages and Compilers SS 2006 / Slide 316

**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**

## Lecture Programming Languages and Compilers SS 2006 / Slide 317

**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.

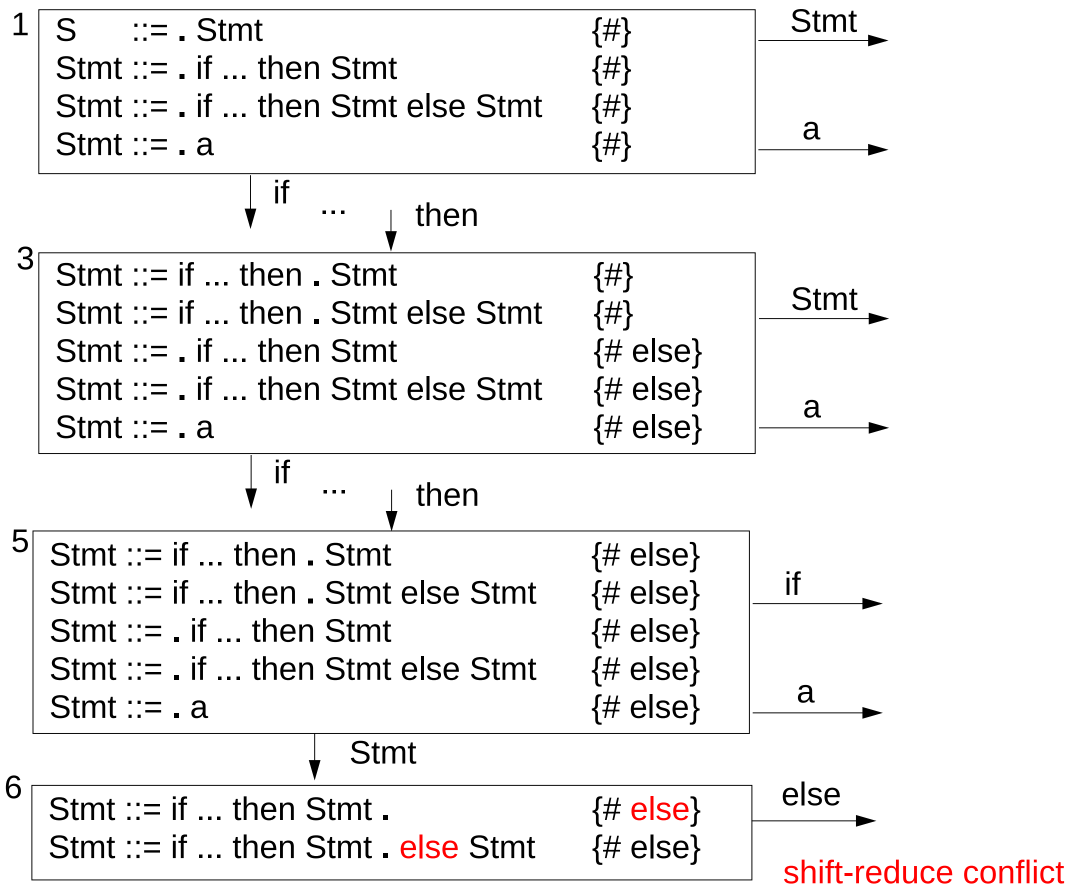
**Suggested reading:**

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



1

| | |
|---|---|
| S ::= **.** Stmt | {#} |
| Stmt ::= **.** if ... then Stmt | {#} |
| Stmt ::= **.** if ... then Stmt else Stmt | {#} |
| Stmt ::= **.** a | {#} |

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} |

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} |

6

| | |
|---|---|
| Stmt ::= if ... then Stmt **.** | {# else} |
| Stmt ::= if ... then Stmt **.** else Stmt | {# else} |

shift-reduce conflict

## Lecture Programming Languages and Compilers SS 2006 / Slide 318

**Objectives:**

See a conflict in an automaton

**In the lecture:**

Explain

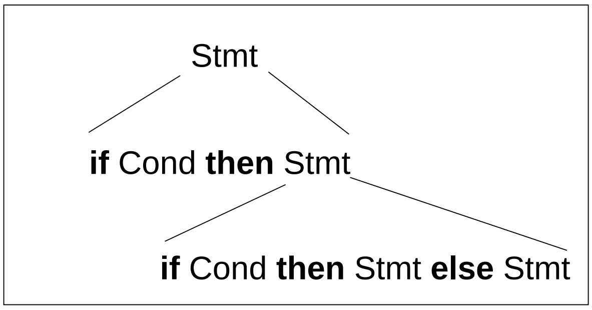
- the construction
- a solution of the conflict: The automaton can be modified such that in state 6, if an else is the next input token, it is shifted rather than a reduction is made. In that case the ambiguity is solved such that the else part is bound to the inner if. That is the structure required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

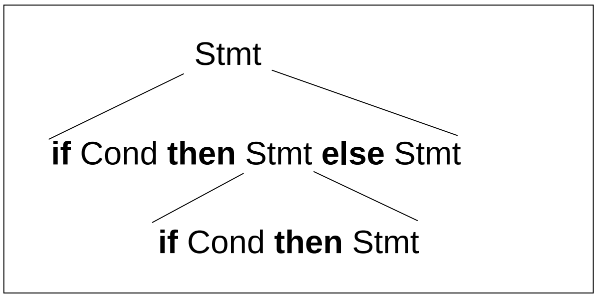
**Suggested reading:**

Kastens / Übersetzerbau, Section 4.3

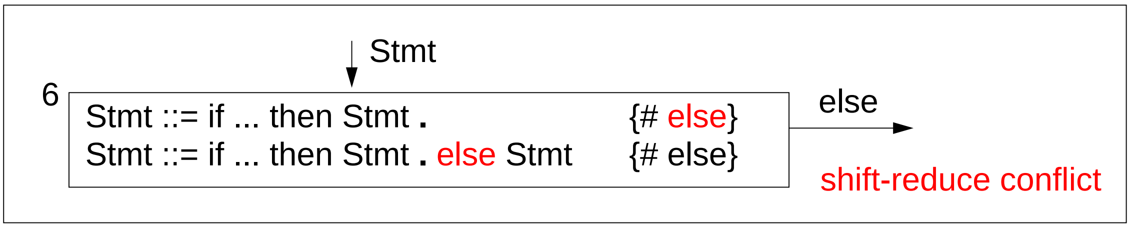
# Decision of ambiguity

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.

## Lecture Programming Languages and Compilers SS 2006 / Slide 319

**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

**LR(0):**

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

**C ::= z .**

**SLR(1):**

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

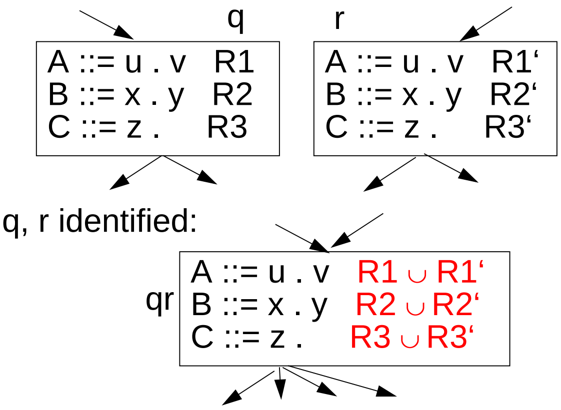
**A ::= u . v**
**B ::= x . y**
**C ::= z .**    **Follow(C)**

**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)**



## Lecture Programming Languages and Compilers SS 2006 / Slide 320

**Objectives:**

Understand relations between LR classes

**In the lecture:**

Explain:

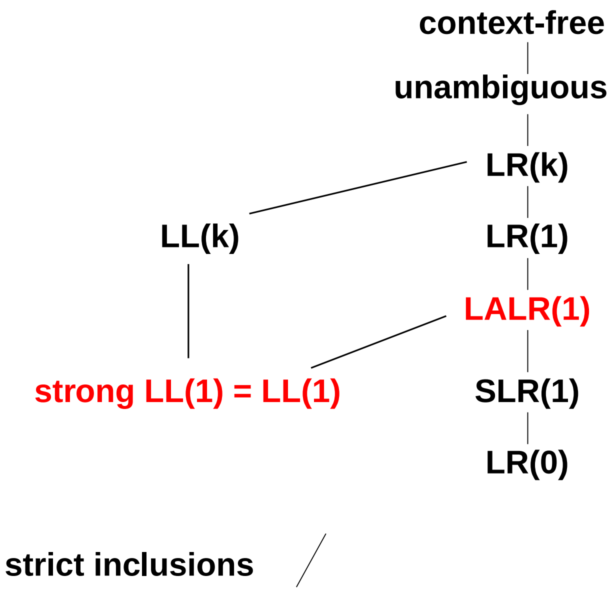
- LALR(1), SLR(1), LR(0) automata have the same number of states,
- compare their states,
- discuss the grammar classes for the example on slide PLaC-3.13.

**Suggested reading:**

Kastens / Übersetzerbau, Section 4.3

**Questions:**

# Hierarchy of grammar classes



## Lecture Programming Languages and Compilers SS 2006 / Slide 321

**Objectives:**

Understand the hierarchy

**In the lecture:**

Explain:

- the reasons for the strict inclusions,

**Suggested reading:**

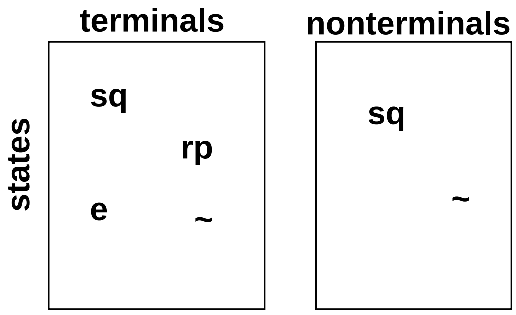
Kastens / Übersetzerbau, Section 4.3

**Questions:**

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

# Table driven implementation of LR automata

LR parser tables



**sq:** shift into state q

**rp:** reduce production p

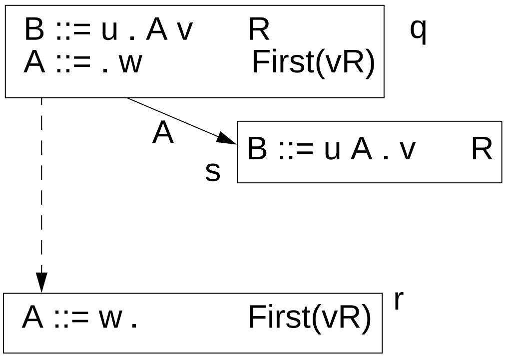
**e:** error

**~:** not reachable

**nonterminal table**

- has **no reduce entries**,
  reduce decision is based on a lookahead **token**
- has **no error entries**,
  errors are already detected when reduction is made

**unreachable entries in terminal table:**
if t is erroneus input in state r, then
state s will never be reached with input t



## Lecture Programming Languages and Compilers SS 2006 / Slide 322

**Objectives:**

Understand properties of LR tables

**In the lecture:**

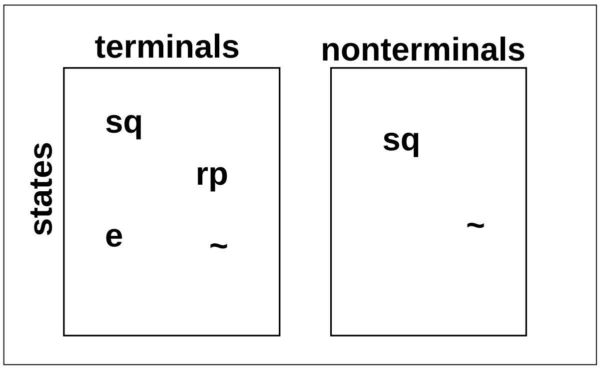
Explanation of

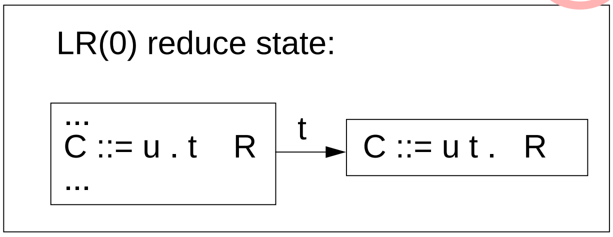
- pair of tables and their entries,
- unreachable entries,

**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.

## Lecture Programming Languages and Compilers SS 2006 / Slide 323

**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 SS 2006 / Slide 324

**Objectives:**

Overview over parser generators

**In the lecture:**

- Explain the significance of properties

**Suggested reading:**

Kastens / Übersetzerbau, Section 4.5

# 3.4 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 SS 2006 / 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 ∈ T* is a correct prefix in the language L(G), if there is an u ∈ T* such that **w u ∈ 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 ∈ T and w, x ∈ T*, if **w is a correct prefix** in L(G) and **w t is not a correct prefix**.

Example: $\underbrace{\texttt{int compute (int i) \{ a = i *}}_{w}\ \underset{t}{\texttt{/}}\ \texttt{c; return i;\}}$

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 SS 2006 / 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

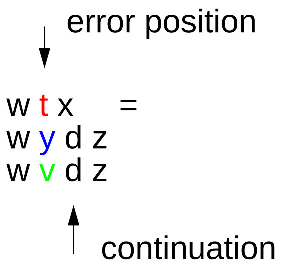
**Continuation point**:

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
a = i * / c;...
a = i *   c;...
```

**delete /**

```
    w    yd  z
a = i * / c;...
a = i *e/ c;...
```

**insert** error id. e

```
    w      y d z
a = i * / c;...
a = i * e  ;...
```

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

## Lecture Programming Languages and Compilers SS 2006 / 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 $\subseteq$ 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 selection of elements in D.

## Lecture Programming Languages and Compilers SS 2006 / 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?

# 3.5 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 provable related to the **documented grammar**;
- can be **mapped to** a suitable **abstract grammar**.

**Objectives:**

Guiding objectives

**In the lecture:**

The objectives are explained.

# 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`**

## Lecture Programming Languages and Compilers SS 2006 / Slide 330

**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. 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

## Lecture Programming Languages and Compilers SS 2006 / Slide 331

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

## Lecture Programming Languages and Compilers SS 2006 / Slide 332

**Objectives:**

How to express restrictions

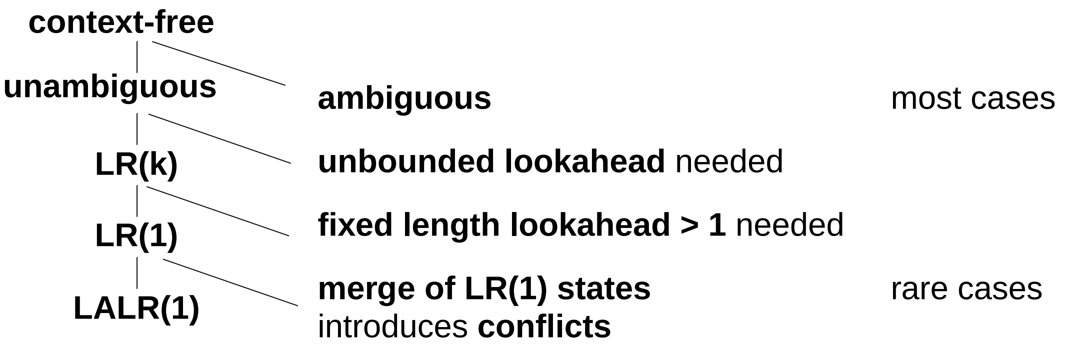
**In the lecture:**

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

**Exercises:**

Discuss further examples for restrictions.

# Reasons for LALR(1) conflicts



Grammar condition does not hold:

context-free
unambiguous
LR(k)
LR(1)
LALR(1)

| | | |
|---|---|---|
| | **ambiguous** | most cases |
| | **unbounded lookahead** needed | |
| | **fixed length lookahead > 1** needed | |
| | **merge of LR(1) states** introduces **conflicts** | rare cases |

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

## Lecture Programming Languages and Compilers SS 2006 / Slide 333

**Objectives:**

Distinguish cases

**In the lecture:**

The cases are explained.

# 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

## Lecture Programming Languages and Compilers SS 2006 / Slide 334

**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.

## Lecture Programming Languages and Compilers SS 2006 / Slide 335

**Objectives:**

Typical situation

**In the lecture:**

Explain the problem and the solution using the example

**Questions:**

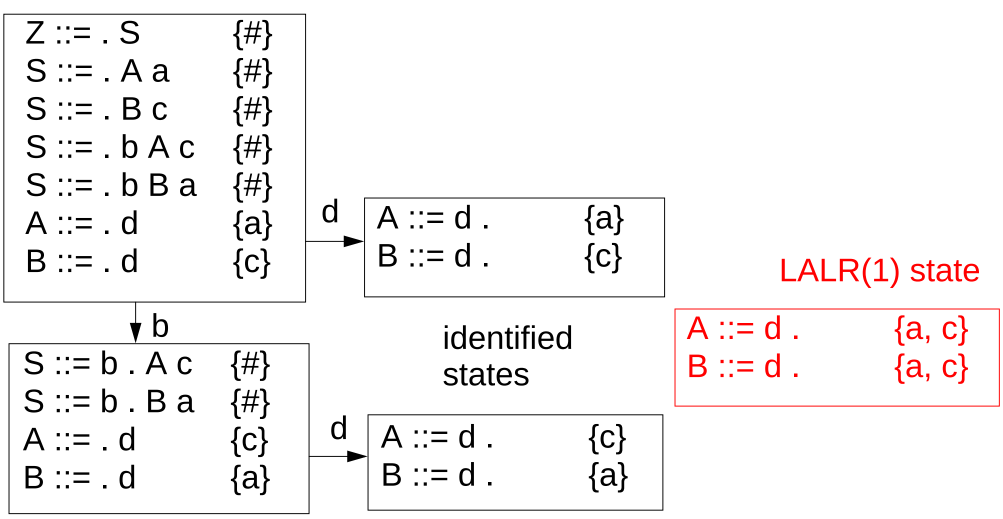
# LR(1) but not LALR(1)

**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



| | |
|---|---|
| Z ::= . S | {#} |
| S ::= . A a | {#} |
| S ::= . B c | {#} |
| S ::= . b A c | {#} |
| S ::= . b B a | {#} |
| A ::= . d | {a} |
| B ::= . d | {c} |

d

| | |
|---|---|
| A ::= d . | {a} |
| B ::= d . | {c} |

b

| | |
|---|---|
| S ::= b . A c | {#} |
| S ::= b . B a | {#} |
| A ::= . d | {c} |
| B ::= . d | {a} |

d

| | |
|---|---|
| A ::= d . | {c} |
| B ::= d . | {a} |

identified
states

LALR(1) state

| | |
|---|---|
| A ::= d . | {a, c} |
| B ::= d . | {a, c} |

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

## Lecture Programming Languages and Compilers SS 2006 / Slide 336

**Objectives:**

Understand source of conflicts

**In the lecture:**

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