3. Context-free Grammars and Syntactic Analysis

Input: **token sequence**

Tasks:

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

Result: **abstract program tree**

Compiler module parser:

deterministic stack automaton, augmented by actions for tree construction

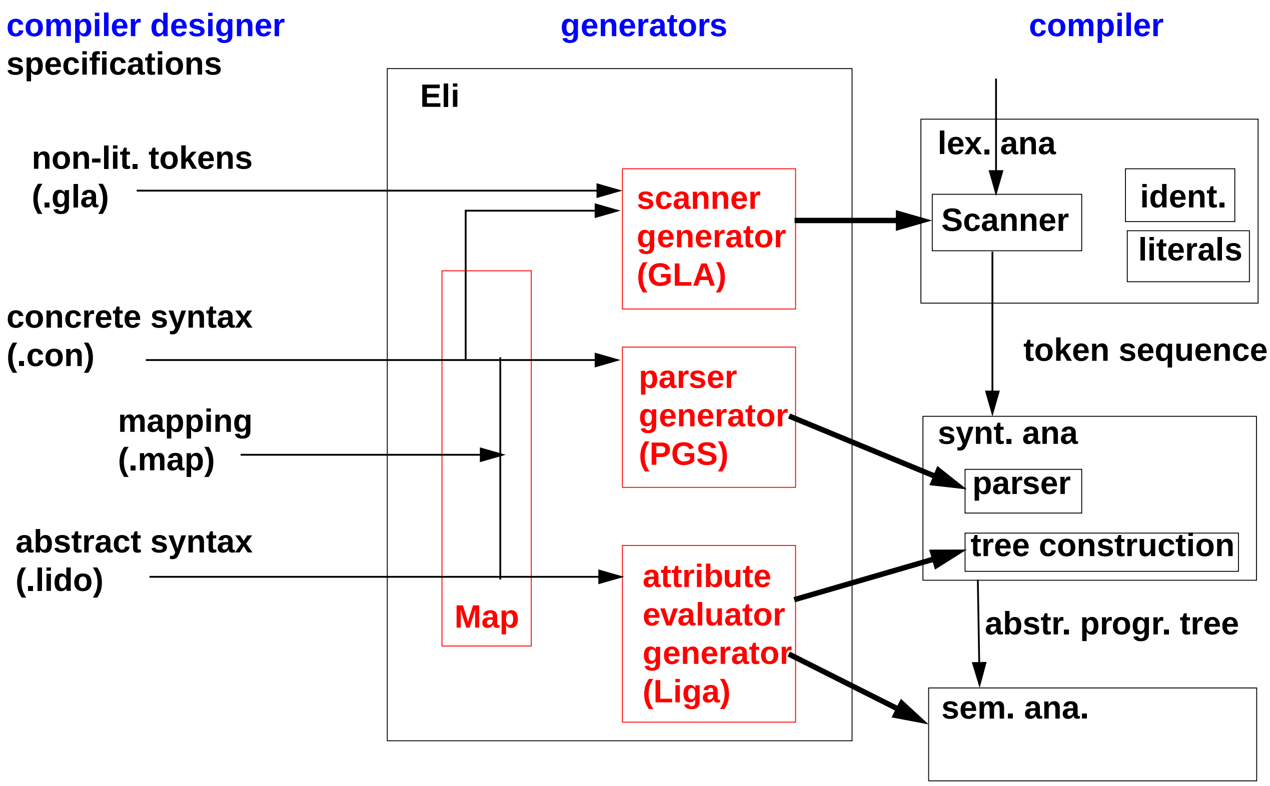
top-down parsers: leftmost derivation; tree construction top-down or bottom-up

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

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

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

Generating the structuring phase from specifications (Eli)



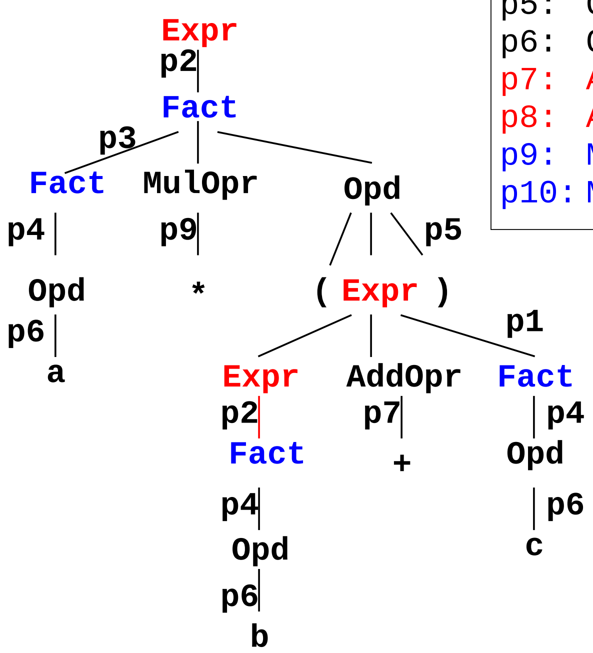
3.1 Concrete and abstract syntax

concrete syntax	**abstract syntax**
- context-free grammar	- context-free grammar
- defines the structure of source programs	- defines abstract program trees
- is unambiguous	- is usually ambiguous
- specifies derivation and parser	- translation phase is based on it
- parser actions specify the tree construction --->	- tree construction
- some chain productions have only syntactic purpose **`Expr ::= Fact`** have no action	no node created
- symbols are mapped **`{Expr,Fact}`** ->	to one abstract symbol **`Exp`**
- same action at structural equivalent productions: **`Expr ::= Expr AddOpr Fact &BinEx`** **`Fact ::= Fact MulOpr Opd &BinEx`**	- creates tree nodes
- semantically relevant chain productions, e.g. **`ParameterDecl ::= Declaration`**	- are kept (tree node is created)
- terminal symbols identifiers, literals, keywords, special symbols	- only semantically relevant ones are kept identifiers, literals
- concrete syntax and symbol mapping specify	- abstract syntax (can be generated)

Example: concrete expression grammar

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

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



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

Patterns for expression grammars

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

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

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

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

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

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

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

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

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

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

```
H ::= Ident
```

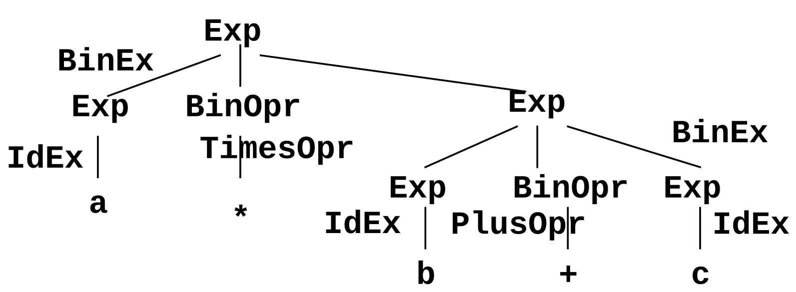
Expressions in parentheses: only derived from the nonterminal of the **highest precedence** level (assumed to be H here); **contain** the nonterminal of the **lowest precedence level** (be A here):

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


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

3.2 Design of concrete grammars

Objectives

The concrete grammar for **parsing**

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

A strategy for grammar development

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

Grammar design for an existing language

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

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

Grammar design together with language design

Read grammars before writing a new grammar.

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

- repetitions
- optional constructs
- precedence, associativity of operators

Syntactic structure should reflect semantic structure:

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

Violated in Pascal:

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

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

Syntactic restrictions versus semantic conditions

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

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

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

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

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.

3.3 Recursive descent parser

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

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

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

Productions for `Stmt`:

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

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

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

Grammar conditions for recursive descent

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

DecisionSet (A ::= u) ∩ DecisionSet (A ::= v) = ∅

with

DecisionSet (A ::= u) := if nullable (u) then **First (u)** ∪ **Follow (A)** else **First (u)**

nullable (u) holds iff a derivation u ⇒* ε exists

First (u) := { t ∈ T | v ∈ V* exists and a derivation u ⇒* t v }

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

Example:

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

non-terminal

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

Computation rules for nullable, First, and Follow

Definitions:

nullable(u) holds iff a derivation u ⇒* ε exists

First(u):= { t ∈ T | v ∈ V* exists and a derivation u ⇒* t v }

Follow(A):= { t ∈ T | u,v ∈ V* exist, A ∈ N and a derivation S ⇒* u A v such that t ∈ First(v) }

with G = (T, N, P, S); V = T ∪ N; t ∈ T; A ∈ N; u,v ∈ V*

Computation rules:

nullable(ε) = true; nullable(t) = false; nullable(uv) = nullable(u) ∧ nullable(v);
nullable(A) = true iff ∃ A::=u ∈ P ∧ nullable(u)

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

Follow(A):
if A=S then # ∈ Follow(A)
if Y::=uAv ∈ P then First(v) ⊆ Follow(A) and if nullable(v) then Follow(Y) ⊆ Follow(A)

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:**

u, v, w ∈ V*
X ∈ N does not occur in the original grammar

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

left-factorization:

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

elimination of direct recursion:

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

special case empty v:

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

LL(1) extension for EBNF constructs

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

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

additional LL(1)-condition:

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

in recursive descent parser:

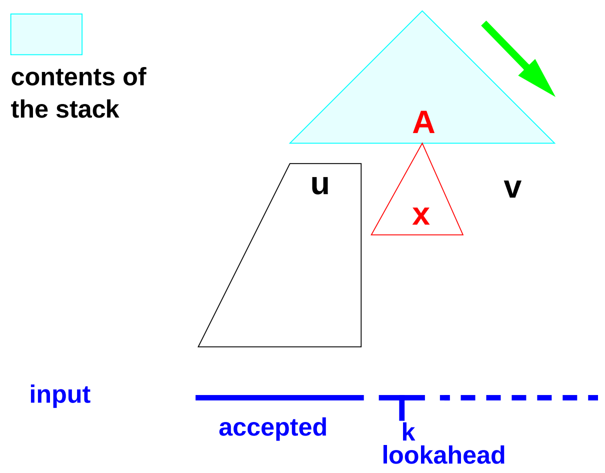
v if (CurrToken in First(u)) { u } w	v while (CurrToken in First(u)) { u } w

Repetition (u)+ left as exercise

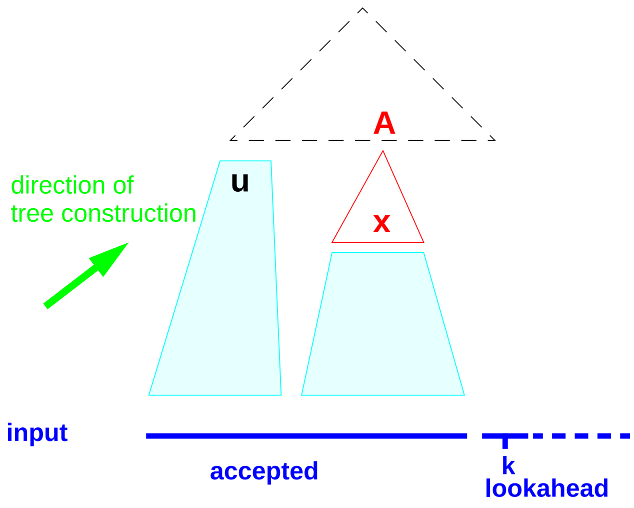
Comparison: top-down vs. bottom-up

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

top-down, predictive
leftmost derivation



bottom-up
rightmost derivation backwards

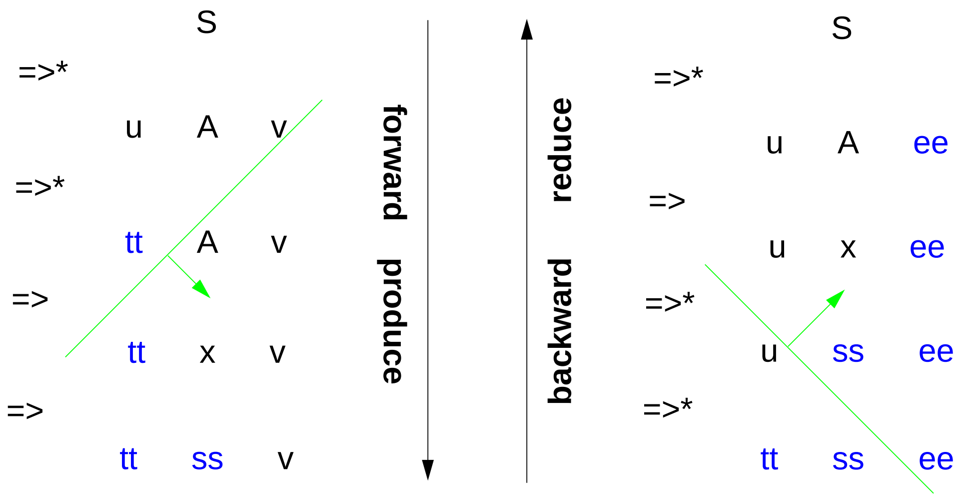


A bottom-up parser has seen more of the input when it decides to apply a production.

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

Leftmost and rightmost derivations

leftmost **rightmost**



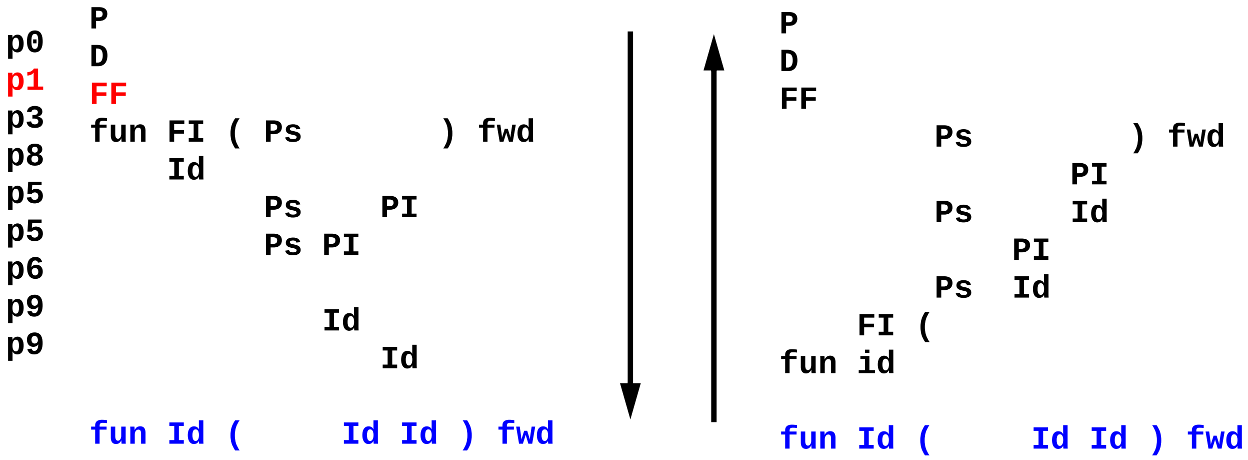
u, v, x ∈ V*

tt, ss, ee ∈ T*

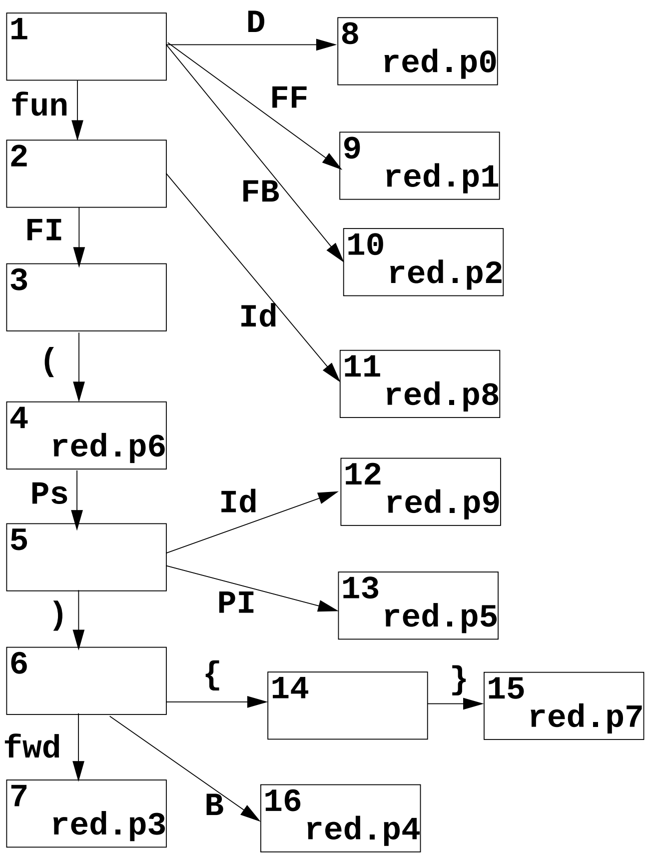
A ∈ N

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

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



LR(0) -Automaton



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

3.4 LR parsing

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

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

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

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

Comparison of LL and LR states:

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

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

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

LR(1) items

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

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

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

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

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

Reduce item:

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

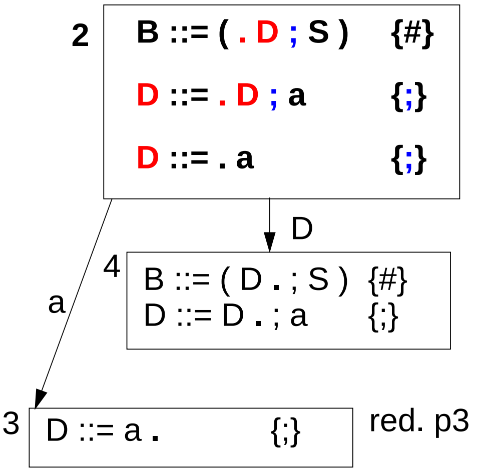
characterizes a reduction using this production if the next input token is in R.

The automaton uses R only for the decision on reductions!

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

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.



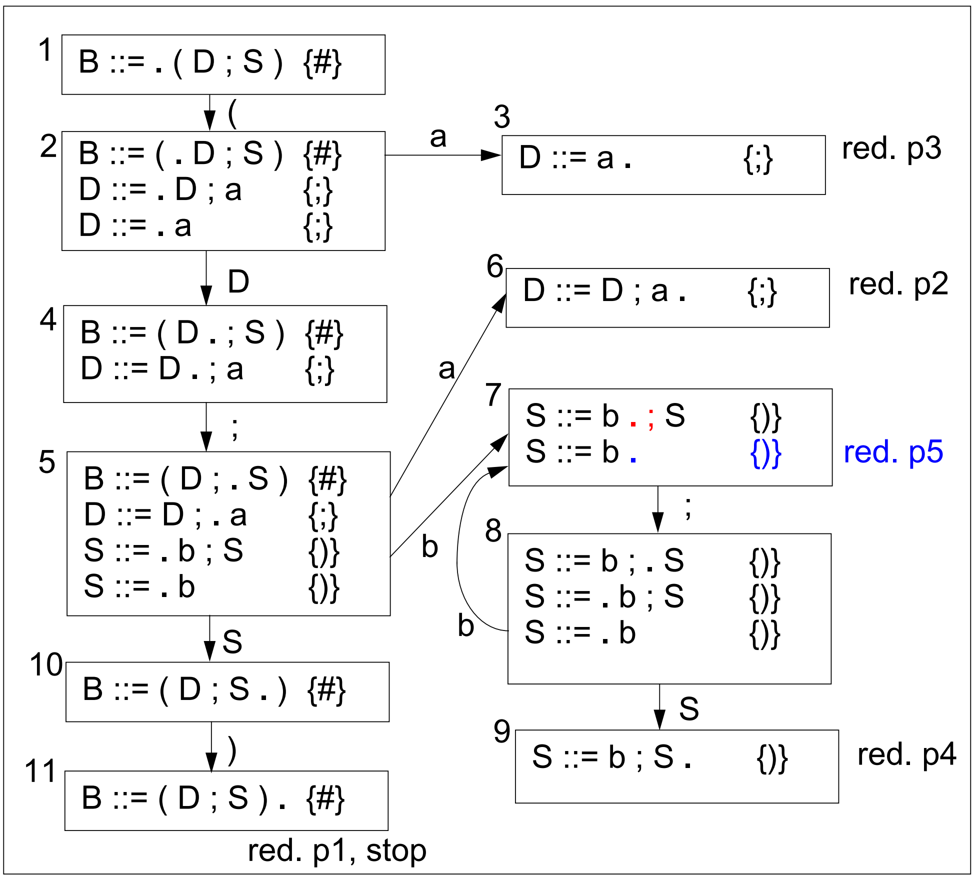
A shift transition is made under
a **token read** from input or
a **non-terminal** symbol
obtained from a **preceding reduction.**
The state is pushed.

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



In state 7 a decision is required on next input:
- if ; then shift
- if) then reduce p5

In states 3, 6, 9, 11 a decision is not required:
- reduce on any input

Construction of LR(1) automata

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

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

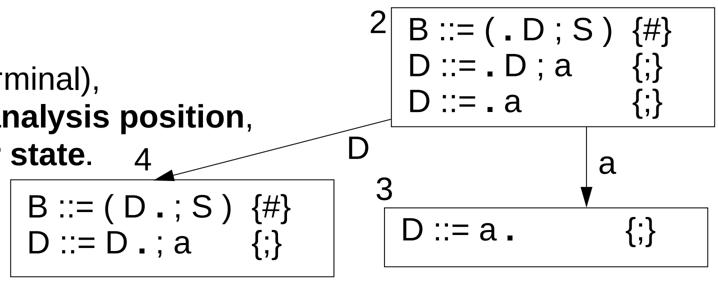
before: 2 B ::= (. D ; S) {#}

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

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

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

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



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

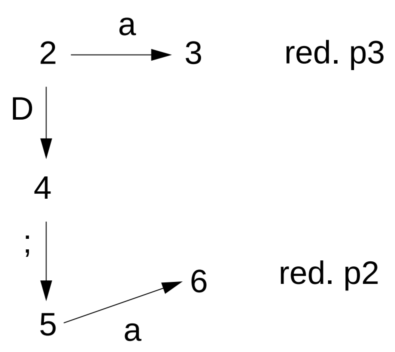
Example:

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	#	

Left recursion versus right recursion

left recursive productions:

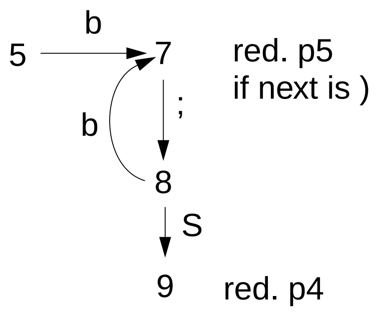
p2: D ::= D ; a
p3: D ::= a



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

right recursive productions:

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



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

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
...
```

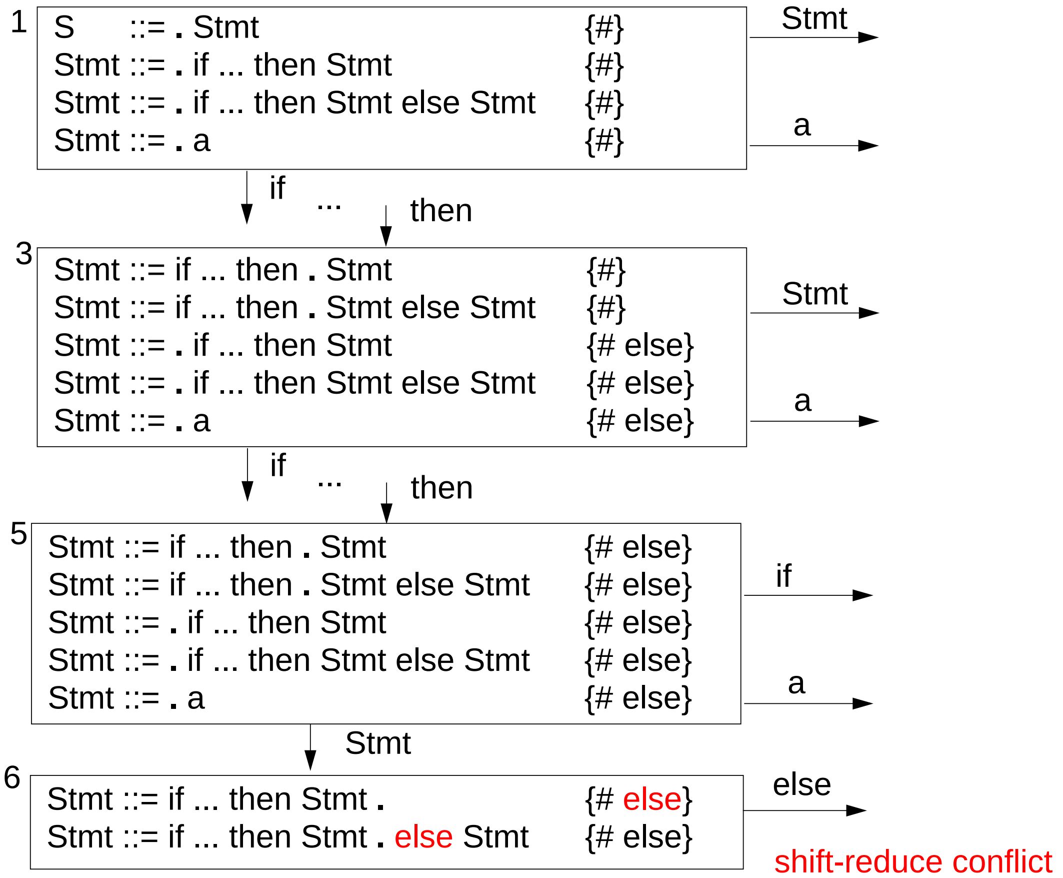
R1, R2 not disjoint

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
...
```

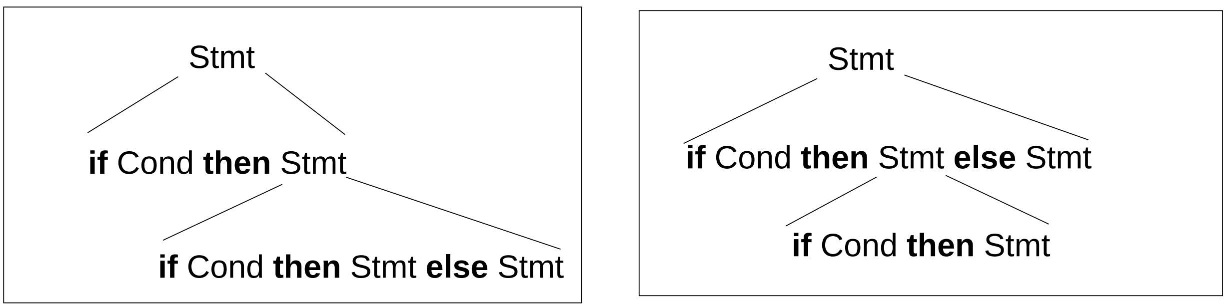
t ∈ **R2**

Shift-reduce conflict for „dangling else“ ambiguity

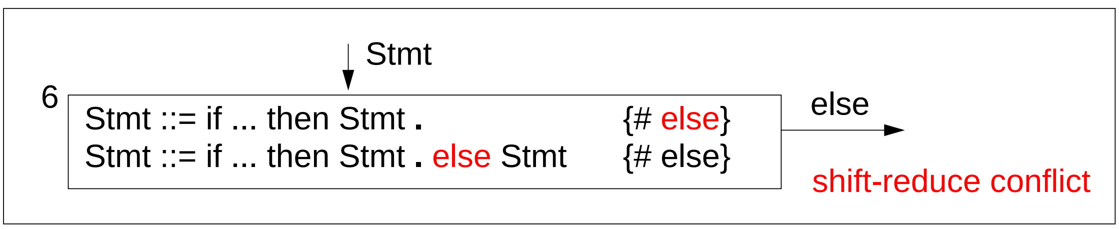


Decision of ambiguity

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.

Simplified LR grammar classes

LR(1):

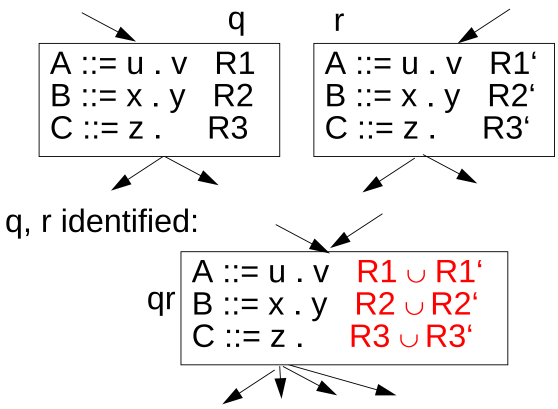
too many states for practical use**,** because right-contexts distinguish many states.
Strategy: simplify right-contexts sets; **fewer states**; grammar classes less powerful

LALR(1):

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

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

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



SLR(1):

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

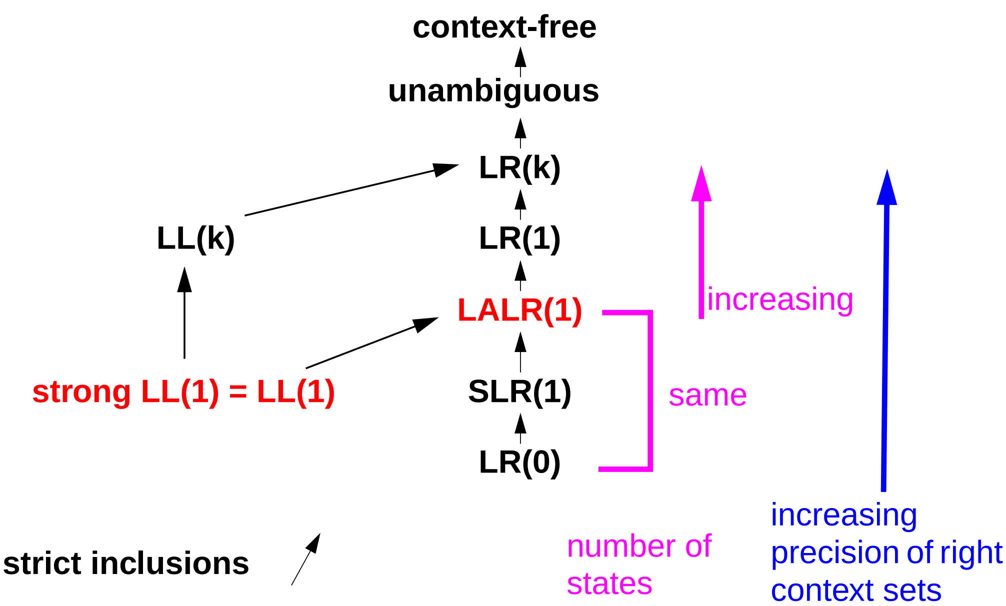
A ::= u . v
B ::= x . y
C ::= z . **Follow(C)**

LR(0):

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

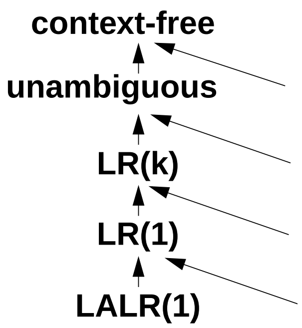
C ::= z .

Hierarchy of grammar classes



Reasons for LALR(1) conflicts

Grammar condition does not hold:



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.

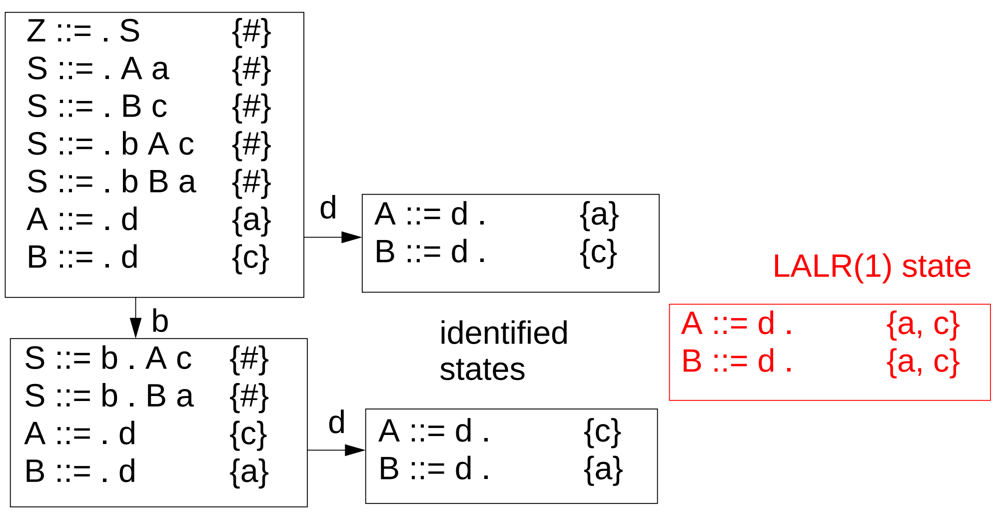
LR(1) but not LALR(1)

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.

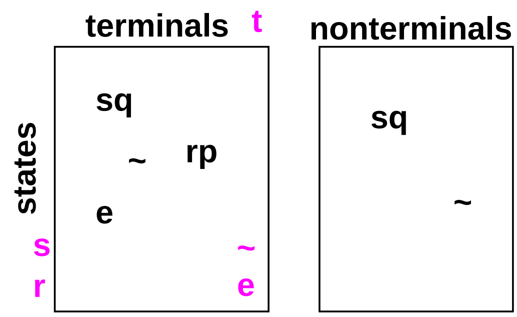
LR(1) states



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

Table driven implementation of LR automata

LR parser tables

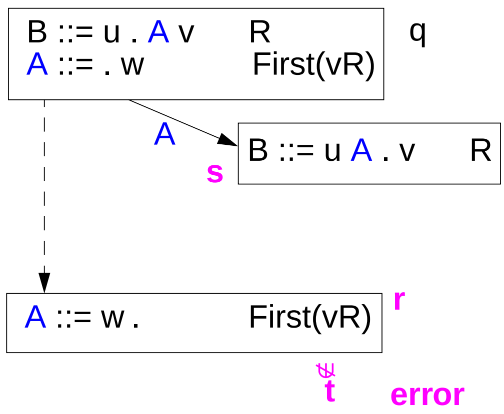


sq: shift into state q

rp: reduce production p

e: error

~: not reachable
don't care

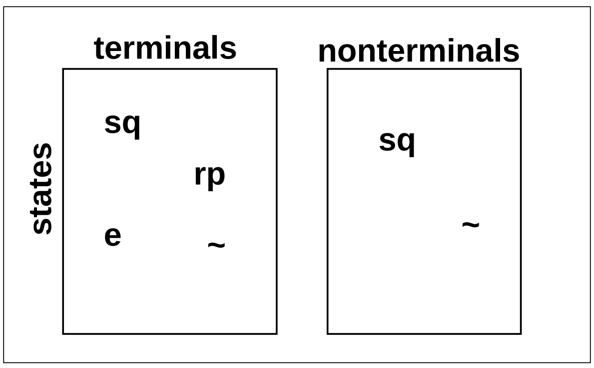


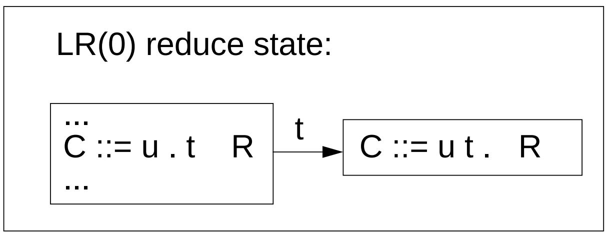
nonterminal table

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

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

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.

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

3.5 Syntax Error Handling
General criteria

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

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:

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

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

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

error position ↓

w t x =
w y d z
w v d z

↑ continuation

Examples:

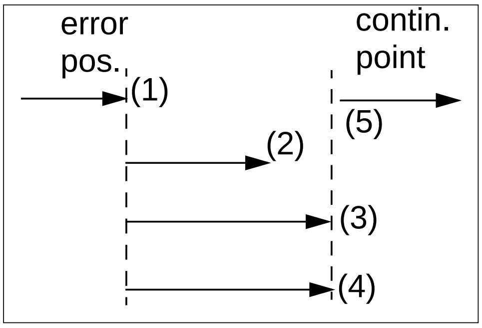
w y d z	w yd z	w y d z
`a = i * / c;...`	`a = i * / c;...`	`a = i * / c;...`
`a = i *   c;...`	`a = i *e/ c;...`	`a = i * e  ;...`
delete /	**insert** error identifier e	**delete / c** and **insert** error id. **e**

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 deletion/insertion of elements in D.