Incremental Parsing

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Contents

1 The problem

Abstract

During syntax-directed editing, a text and a corresponding parse tree exist. When the user makes a change in the text, it is desirable to update the parse tree in an incremental way, in stead of reparsing the whole text. We will do this by means of an island parser that allows us to start parsing at any place in the text, and to parse in both left and right direction until a tree is found that fits into the existing parse tree. The island parser is presented as an adaption of the Earley parser.

Notation and conventions

In this section, we[1] will give some definitions that we use.

A **terminal** is a character in {a..z} followed by an arbitrary sequence of characters, or the empty sequence ε. For example, 'apple' and 'aA94$@' are terminals. A **nonterminal** is a character in {A..Z}, followed by an arbitrary sequence of characters. So 'Apple' is a nonterminal. A **symbol** can be either a terminal or a nonterminal. Lower case Greek characters (like α,β,σ, excepted ε since it is the empty sequence) stand for an arbitrary sequence of symbols. Two symbols in a sequence are separated by a white space (' '). To avoid confusion, we do not allow spaces in symbols.

For T_1 and T_2 being terminals, we can **concatenate** T_1 and T_2. We write $T_1 \cdot T_2$. Two terminals are concatenated by simply sequencing them. For example, golf·club = golfclub.

If N is some nonterminal, and σ is some sequence of symbols, then 'N ::= σ' is a rule. So 'P ::= a b c', 'S ::= ε' and 'Apple ::= a51 Apple Bear' are rules. A "|" in a rule has a special meaning: N ::= α | β is short for two rules: N ::= α and N ::= β. A grammar is a set of rules. For example { S ::= S S, S ::= x, S ::= ε } is a grammar.

Assume we have a grammar G. If N is a nonterminal, α,β are arbitrary sequences and there is a rule N ::= σ in G, then α N β ⇒ α σ β is called a **derivation step**. If α ⇒ β ⇒ .. ⇒ γ or α=γ then α ⇒* γ. If there is a nonterminal N such that N ⇒* S_1 .. S_n, and each S_i is a terminal, then we say that G **produces** $S_1 \cdot S_2 \cdot \ldots \cdot S_n$. L(G) is the set of all sequences that are produced by G.

Example: take G={S ::=a M b M, M ::= p | q}.

Now the following holds: S ⇒ a M b M ⇒ a p b M ⇒ a p b q. Therefore S ⇒* a p b q,. and we say that G produces apbq.

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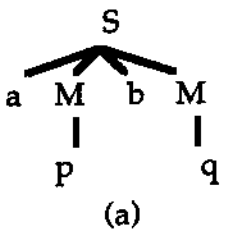
[1] 'I' would be better, but it seems a nonwritten rule to use 'we'. After all, it is reassuring to know that someone else has exactly the same ideas.

In each derivation step, one nonterminal is substituted by a sequence of symbols. But if different nonterminals occur in the same sequence of symbols, it does not matter in what order these nonterminals are replaced. In the example, we can also make a derivation $S \Rightarrow a\ M\ b\ M \Rightarrow a\ M\ b\ q \Rightarrow a\ p\ b\ q$. There is no real difference between these two derivations: in both cases the first M is replaced by p, and the second by q.

The derivation we make to proof that $N \Rightarrow^* \sigma$ can be put in a picture called a **parse tree**. A parse tree is a (directed) acyclic graph. The direction is implicit downwards. A node in a parse tree has children. Unlike acyclic graphs, these children are ordered in a way corresponding to their ordering in the rule. In the pictures, the children are placed under their parent in order from left to right. Each symbol in a derivation has a corresponding symbol in the graph. If, in a derivation, S_i is substituted by $S'_1 .. S'_n$, then S_i gets children $S'_1 .. S'_n$ in this order.
The parse tree of our example looks as follows (a):



(a)

Each node in such a parse tree has a symbol, called the **sort** of the node.
Given a grammar G and a sequence of terminals σ, an algorithm deciding whether there is an N with $N \Rightarrow^* \sigma$ is called a **recogniser**. If the algorithm returns a parse tree it is called a **parser**. If, for some N and σ, there are two derivations $N \Rightarrow^* \sigma$ with different *parse trees*, we say that σ is **ambiguous**.

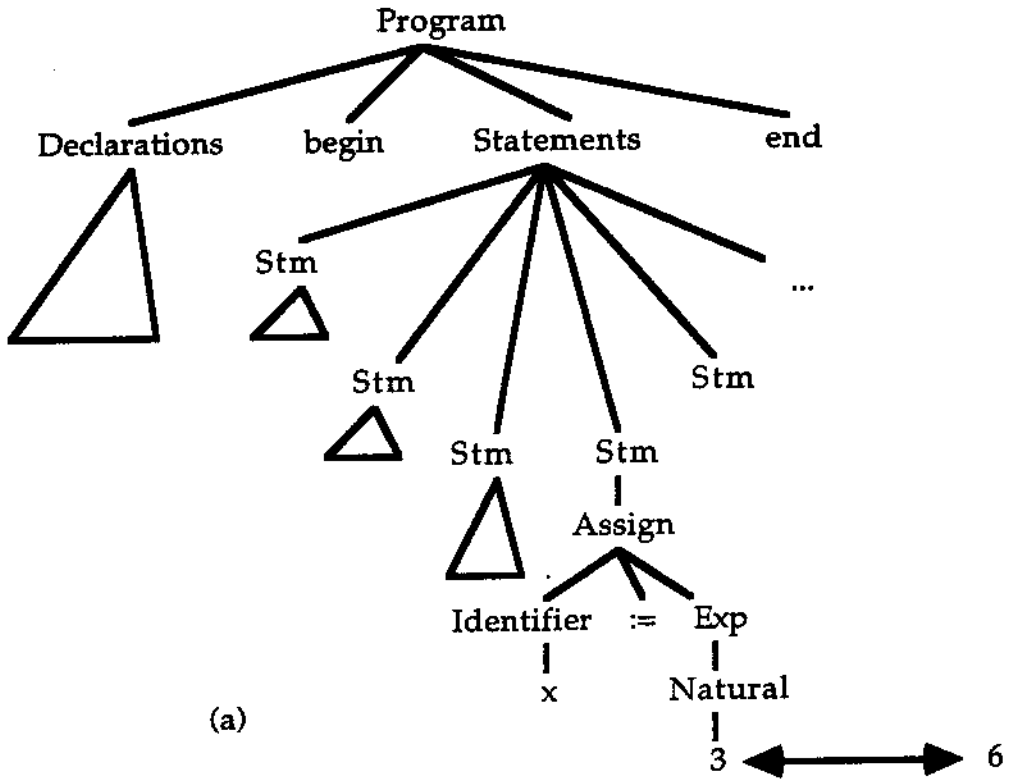
Text and parse trees

We assume the reader to be familiar with syntax directed editors. In these editors, the user works with a kind of text editor. The editor knows the grammar the user is working with, and checks whether the text the user types is correct. For example, if the used grammar is Pascal, the editor will only allow correct Pascal text to be entered. Of course, there are moments when this is not possible. For example if the user wants to type 'begin', and he types the first 'b' of it, we do not yet have a correct Pascal text.
Usually, syntax directed editors update the parse tree as soon as possible. For example the Synthesizer Generator and the Generic Syntax-directed Editor ([DK90]) work in this way. This can be useful for several reasons:

- The user can be informed as soon as possible about syntax errors in his text.
- It is easy to provide parse tree dependent commands to the user, for example a 'go to parent node' or a 'pretty print' command.
- When the text the user typed is needed in a parsed format, the parse tree is directly available.

Incremental parsing

In most cases, the user edits a small part of his text. Usually, these small changes have little effect on the parse tree. For example, when the user changes the statement 'x:=3' in 'x:=6' in a Pascal editor, only the assignment has to be changed. In a picture, this looks as follows (a):



(a)

As we can see in the picture, to correct the tree, only the 3 has to be replaced by a 6. We do not have to look at the other nodes. However, it is not always as easy as in this picture. Consider the following example.

Grammar:

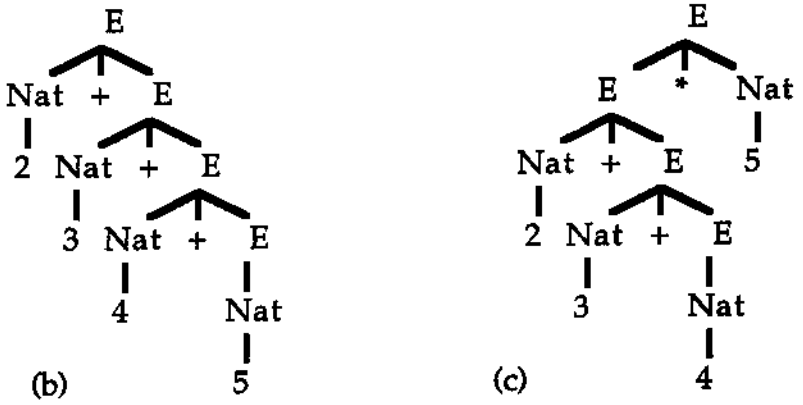
E ::= Nat + E | E * Nat | Nat
Nat ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

Note that in this grammar, a * multiplies anything before it with the number directly following it.

When the + is changed into an * as in

2+3+4+5 -> 2+3+4*5

the parse tree before the edit looks like (b), and the one after the edits like (c).



The change of only one character therefore changes the whole tree up to the top node. In general, the work involved in correcting the parse tree depends on the grammar and the specific edit actions.

The job of updating the parse tree with as little work as possible is called 'incremental parsing', and is the subject of this thesis.

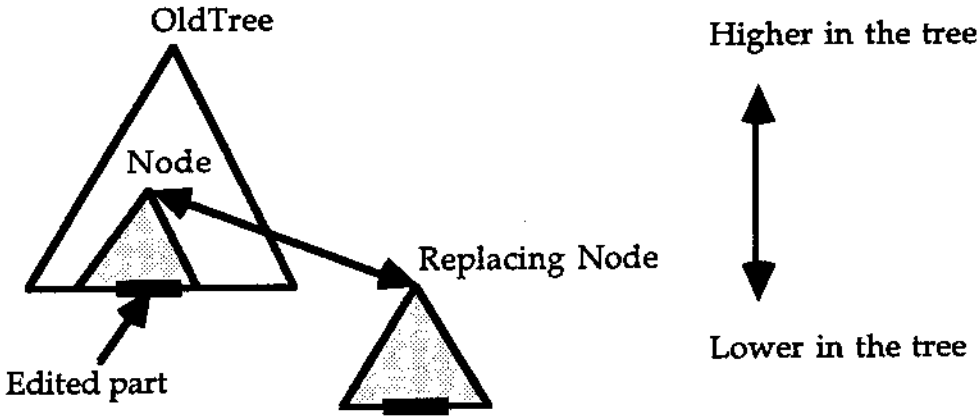
Overview of the thesis

In chapter 2, we will give one way of updating the parse tree after an edit action. The algorithm for correcting the parse tree needs to decide about what is the right place to do a correction. There are various ways to make this decision. One way to make an algorithm for deciding it is given in chapter 3. We will show that in general, the decision is at least as hard as a recogniser. And after all, we need to parse if we found the place to do a correction. So it seems better to make an *island parser* doing both jobs in one time. This is done in chapter 4-6. In chapter 7, we consider some optimizations.

2 Introduction to incremental parsing

Finding a node to replace

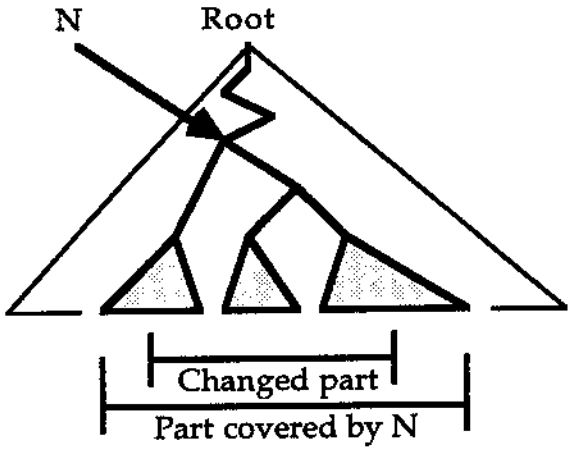
Assume that the user of a syntax-directed editor has changed a part of the text. This text can be found at the leaves of the parse tree. We want to replace at most *one* node to correct the parse tree. The reason for this is that although it may be possible to replace a number of smaller trees, it is not clear to us how an algorithm to do this should be like. So, we have the following picture (a).



(a)

There is always such a replacing node if there is a correct parse tree: the root node. However, replacing that node means that we have to make a new root node, and this implies reparsing of the whole text. This is not really incremental parsing. So we prefer a lower node than the root node.

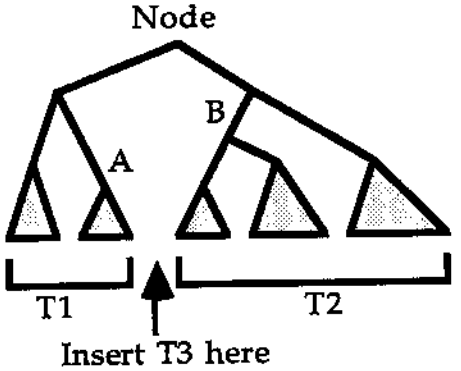
How do we find the lowest Node that has to be replaced? In general, this is a difficult problem. We choose for the following solution: Start at a certain node, and try to replace it. If this fails, try to replace the parent of the node.



(b)

What is a useful start node? Consider picture (b). When the user has changed some text, the characters he changes correspond to some leaf nodes in the parse tree. The node we are looking for must at least cover the leaves that are changed. We find this node by finding the lowest common parent of the leftmost and the rightmost leaf that has been changed. In the picture, this is N.
If there is no correct parse tree, we can not do the correction step. In stead, we place the new text as unparsed text under the N node of the old parse tree, just to have the parse tree correspond with the text. We will have to wait for more corrections until we can make up the new parse tree. We remember the sort of the old node, because we only may place trees of that sort at that place in the parse tree without problems. For example when the user again edits this text, and retypes the old text, we can put back the old parse tree at the same place.

If the user does a plain insert, without replacing old leaves of the parse tree, we have a problem with finding the start node. In this case, no leaves have changed, so there is no common parent node. But for our algorithm, we still need a start node. In a picture, the problem looks like (c). T1 and T2 is the text under the lowest common parent node of the leaf directly at the left and right of the insertion point. To choose Node should be the worst choice, since T3 might be placed under node A, but giving Node as the edit node would prevent us from replacing A.



(c)

We solve this problem by just taking the parent of the leaf at the left of the edits as the edit node, node A in the picture. But this can be the wrong choice, if T3 appended to T2 could make a new B node. In this case, we are parsing text T1 while this could be avoided by just choosing the other node. But as long as we have no better solution, this seems the only solution.

An algorithm for incremental parsing

With the ideas of the previous sections in mind, we can give an algorithm for incremental parsing. We start looking at the lowest node considering only the last edit action. Previous edit actions have been handled already, and it is useless to hope that the last edit action will solve the unparsed pieces in the parse tree, since previous edit

actions may get important automatically when they get covered during the search for the node that has to be replaced.
In this specification, we first place the unparsed text in the tree. Thereafter, we try to remove the unparsed text from the tree.

```
inc_parse (last edit action)
      /* first find the lowest shared parent node of last action */
     if only insert has been done in last edit action then
          P := parent of the leaf direct at left of insert point
     else
          L := leftmost leaf that has been changed in last action
          R := rightmost leaf that has been changed in last action
          P := lowest common parent of L and R
     fi
     Text := the text covered by P
     replace P by unparsed Text of the same sort as P
      /* and now try to remove the unparsed text from the tree */
     loop
          C := text covered by P
           /* Now decide the allowed sorts at replace point P */
          if P=root node
          then TopSort := 'any' else TopSort := sort of P fi
          result := CheckForTree(C,TopSort)
          if result=a parse tree
          then
               replace tree at P by that parse tree
               return     /* changes inserted in tree */
          elseif result = 'failure' or P=root node
          then return /* could not make new tree */
          fi
          P:=parent of P
     end  loop
```

CheckForTree can be described as follows. A sequence of terminals T_1 .. T_n is a substring of L(G) $\Leftrightarrow \exists\ \rho,\sigma$ such that $\rho \cdot T_1$ .. $T_n \cdot \sigma$ is in L(G). We call ρ,σ invented. If T_1 .. T_n is in L(G), it is not necessary to invent symbols. TopSort is required nonterminal (in the parse tree, we can only replace a node by another node with the same top sort).

```
CheckForTree (Text,TopSort)
     if a parse tree with right TopSort for Text exists
     then return that parse tree
     elseif Text is not a substring of L(G)
     then return 'failure'
     else return 'more-context'
     fi
```

The test for 'failure' is needed in the case that the user is editing in a text for which no parse tree exists. In such cases, we want to stop trying to make a correct parse tree as soon as possible, and not go on trying parent nodes until we are at the root of the parse tree.

In chapter 3, we have separate solutions that can check if we are in a successful, failure or more-context situation or not. In chapter 4, an integrated solution is presented. The island parser only needs the context, (the new covered text *without* the old covered

text) and not the whole text to decide about parse trees and failures. Therefore, the CheckForTree call looks a little different in that case.

How hard is CheckForTree?

With the following algorithm it is shown that the CheckForTree algorithm in general is as hard as the membership question for context-free grammars (the question 'is w∈G' with G such a grammar):

```
is-element-of (w,G)  /* decide if w∈G */
      if CheckForTree(w,'any') is a parse tree
      then return 'accept'
      else return 'reject'
      fi
```

It is clear that is-element-of returns 'accept' if w can be parsed starting with the start nonterminal of G. Furthermore, CheckForTree can never return a parse tree when this is not the case. In that case, is-element-of returns 'reject'.

3 Partial solutions for CheckForTree

The CheckForTree algorithm

In this chapter, we present some partial solutions for implementing the CheckForTree as described in chapter 2. CheckForTree now gets the following form:

```
CheckForTree (Text,TopSort)
     if there is a Test(Text,TopSort)='failure'
     then return 'failure' fi
     if there is a Test(Text,TopSort)='more-context'
     then return 'more-context' fi
     return parse(Text,TopSort)
```

The strategies to choose a test can differ. It depends a bit on the price (in calculation time) of the different tests, and their chance to return a useful result. How do our tests look like?

Some non-partial but expensive tests

Since CheckForTree has to be certain about the case, as it only can return 'failure', 'more-context' and a parse tree, we need to do a non-partial test in the case that all partial tests failed. An obvious test uses the substring parser ([RK90]). This substring parser makes parse trees given a substring of L(G) by inventing context symbols. It does not seem hard to adapt their substring parser such that it returns information about the need to invent symbols.

```
Test_substring (Text,TopSort)
     <Result,TokensInvented> := substring_parse(Text,TopSort)
     if Result=a parse tree then
          if TokensInvented
          then return 'more-context'
          else return nil /* Correct tree exists */
          fi
     else return 'failure'
     fi
```

It does not seem very hard to adapt the substring parser such that it returns a tree of Sort if a *normal* parse of the text is possible. This way, we do not need to do a normal parse after the test. If this is done, we can make the following test, which decides in *all* cases:

```
CheckForTree' (Text,SortTop)
     <Result,TokensInvented> := substring_parse(Text,TopSort)
     if Result = a parse tree then
          if TokensInvented then return 'more-context'
          else return Result fi
     else return 'failure' fi
```

These tests all are quite expensive in the case that a parse at the root is needed because of a small change, like in the second example of chapter 1. This is especially the case since these tests each time reparse the total Text, and do not reuse results from previous parses. There are two solutions for this:
- Try cheaper tests first, avoiding parse actions.
- make a parser that reuses the previous work.

The last solution is worked out in chapter 4-7. We will now consider some examples of the first solution.

Partial testing without parsing

Idea 1

The idea behind the following test is to check whether the nonterminal Sort can produce all symbols in the Text. If this is the case, a parse might succeed, but we cannot be sure of this, so we return nil, forcing a parse of the test. If one or more symbols cannot be produced by the Sort nonterminal, a parse for this nonterminal will fail. But maybe another nonterminal higher in the parse tree can help.

```
Test_CharClass (Text,Sort)
     if set of symbols in Text ⊆ ProducedSymbols(Sort)
     then return nil    /* parse might succeed? */
     else return 'more-context' fi
```

ProducedSymbols(Sort) is a set containing all the symbols that Sort can produce: ProducedSymbols (N) = { S | N $\Rightarrow^*$ α S β }. In the special case that Text only contains terminals, this set can be restricted to the terminals in it.

Idea 2

Another idea is to check for standard combinations of symbols. For example, an '(' is usually accompanied by a ')'. Caution is needed for example in the if-then and if-then-else case. The if needs a then, but not an else. But when you see an else, there surely is an if and a then. For the resulting test, we need a multiset and some operations on it:
A **multiset** is a kind of set, but elements can occur multiple times. So {1,1,1,1,2,2} is a multiset, and it is *not* equal to {1,2}. The ordering is not important, so it is equal to {1,1,2,2,1,1}. Furthermore, we have the following operations:
M - x: remove one occurrence of x from M, if there is such an x. Otherwise do nothing.
M + x: add x to M once.
$|M|_x$: the number of occurrences of x in M.
$M1 \cap M2 = M$ with $|M|_x = \min(|M1|_x, |M2|_x)$ for each x
$M1 \cup M2 = M$ with $|M|_x = \max(|M1|_x, |M2|_x)$ for each x
$M1 \subseteq M2 \Leftrightarrow |M1|_x \leq |M2|_x$ for each x
$M1 - M2 = M$ with $|M|_x = |M1|_x - |M2|_x$ for each x (only possible if $M2 \subseteq M1$)

Examples:

$\{2,2,3,4\} - 2 = \{2,3,4\}$
$\{2,2\} + 2 = \{2,2,2\}$
$\{1,2,3,4\} - \{1,2,3\} = \{4\}$
$\{1,2,2,3,3,4\} - \{1,2,3,4\} = \{2,3\}$
$\{1,2,3\} \cap \{2,4\} = \{2\}$
$\{2,2,2\} \cap \{1,2,2\} = \{2,2\}$
$\{1,2,2,2,3,4\} \cap \{2,2,3\} = \{2,2,3\}$

First, we make a multiset for each rule in the grammar. These multisets have to contain all the terminals in that grammar rule.

Example
syntax of G:

S ::= a b S c a T d	(1)
S ::= b e T f g	(2)
S ::= b a h	(4)
T ::= a u b e	(3)

Now the multisets become:

M_1= {a,b,c,a,d}
M_2= {b,e,f,g}
M_3= {a,u,b,e}
M_4= {b,a,h}

These sets intend to express what tokens have to be produced in one nonterminal. If we want to recognise a nonterminal successfully, all its symbols have to appear in the text, otherwise it cannot succeed. The idea is to see the text as a symbol multiset SM of symbols. We try to remove all symbols from SM. If we don't succeed, then it is certain that the nonterminal can not be produced.

We take a symbol from SM, and check which symbols are accompanied by this symbol, with the multisets M_1 to M_4. Now we strip all these symbols from SM.

Example
Syntax: G as in the previous example.
Text: "a b d c a f e d" → SM = {a,b,d,c,e,d,f,a}
Question: is this text in L(G)?
Approach:

1 Take a symbol from SM, say c.
2 The only set that contains a 'c' is M_1, therefore remove all symbols that are in M_1 from SM. This gives SM={e,d,f}
3 Take another symbol from the new SM. For example f.
4 The only set that contains an 'f' is M_2.
5 Subtract M_2 from SM. This cannot be done, since not $M_2 \subseteq$ SM. Therefore we can be sure that "a b d c a f e d" is not in L(G).

In some cases there are more choices. If we had chosen an 'a' in step 1, both M_1, M_3 and M_4 told something about an 'a'. In that case the only thing you can be sure of, is that a 'b' is needed, because any of the 3 multisets contain a 'b'. Anyway, it is

important which symbol is chosen from SM. When there is only 1 set containing the chosen symbol, it's easy, therefore the first check should be for this case. This idea was used in the example. Difficulties arise when this is not the case, as shown in the following example.

Text: "a e b e a" → FM = {a,e,b,e,a}
Question: What symbol is the best to choose from FM?
We can choose 3 symbols in this case: a,b and e. What are the consequences?

Chosen symbol	Multisets containing that symbol:	∩	∪	∪−∩
a	1,4	{a,b}	{a,b,c,d,h}	{c,d,h}
b	1,2,4	{a,b}	{a,b,c,d,e,f,g,h}	{c,d,e,f,g,h}
e	2,3	{b,e}	{a,b,e,f,g,u}	{a,f,g,u}

What happens if we choose an 'a', for example? Then we can be sure that there has to be a 'b' symbol in SM. Thus we remove both 'a' and 'b' from SM. But there are other symbols that could be produced (this is the '∪−∩' set). The view we take is to note them as 'possibly stripped', and remove them from SM. We note them as 'possibly stripped' because another symbol, that is left in SM, may need it. In that case it can find it in the possibly-stripped-set.

With this possibly-stripped approach in mind, a useful tactic is to choose the symbol with the smallest number of elements in the '∪−∩' set. In the case that only one multiset contains the symbol, it is Ø, so it's a good choice in this case, too. In the case of example 9, symbol 'a' is chosen with this tactic (the set {c,d,h} corresponding to choosing an 'a' contains 3 elements, other choices give 4 or 6 elements). The test becomes:

```
Test_Sets (Text, Symbol)
     SM := multiset containing the symbols in Text
     PossiblyStripped := Ø
      /* As long as there are symbols not stripped */
     while SM ≠ Ø do
          for each x in SM do
               Intersection_x := ∩ {M_i | x ∈ M_i}

               Union_x := ∪ {M_i | x ∈ M_i}
               Difference_x := Union_x - Intersection_x
          od /* Now select minimal difference */
          k := a number such that |Difference_k| is minimal
           /* Strip symbols in the chosen intersection from SM. */
          for each x in Intersection_k do
               Intersection_k := Intersection_k - x
                /* Check if symbol appears in SM*/
               if x in SM
               then /* Yes, strip it */ SM := SM - x
               else /* No, perhaps moved to PossiblyStripped? */
                    if x ∈ PossiblyStripped then
                         /* Yes, strip it there because now */
                         /* We're sure that token is needed */
```

```
                    PossiblyStripped := PossiblyStripped - x
                else
                    /* Symbol isn't there! parse will fail */
                    return 'more-context'
                fi
            fi
        od
        /* All symbols in intersection stripped.*/
        /* Now move symbols that can be stripped to PossiblyStr*/
        for each x in Difference_k do
            if x ∈ SM then
                PossiblyStripped := PossiblyStripped + x
                SM := SM - x
            fi
        od
    od
    /* Everything went ok, nothing concluded.. */
    return nil
```

Idea 3

We will describe the following test only briefly. For each nonterminal in the grammar, we can make a *regular expression* that can recognise 'about the same' as the nonterminal in the grammar. This approximation can never be perfect, since there context-free grammars are more expressive than regular expressions ([HU79] p.61). We aim for a regular expression that accepts as little too much as possible (but never to little) . Some examples of the conversion that can be done:

Definition: $\Sigma_N = \{ S \mid N \Rightarrow^* \alpha S \beta \}$

Grammar	example approximations with a regular expression
S ::= aS | b	$RE_S = a^*b$
S ::= aSb | c	$RE_S = a^*cb^*$
S ::= aSb | c	$RE_S = c \mid aa^*cb^*b$
E ::= (E) | E+E | E*E	$RE_E = '(' \Sigma_E^* ')' \mid \Sigma_E^* '+' \Sigma_E^* \mid \Sigma_E^* '*' \Sigma_E^*$
P ::= aPbPc | d	$RE_P = a^*d[b\Sigma_P^*c]^*$

Hint for conversion of the last: convert P ::= aPbΣ_P*c | d instead.

Now, we make the following test. We return 'more-context' if the Text is not produced by the regular expression that we made for Symbol: we made that expression produce more than really is produced by Symbol, so if our regular expression does not produce the text, Symbol certainly won't.

```
Test_RegExp (Text, Symbol)
    if Text is produced by RE_Symbol
    then return nil                    /* Text seems ok? */
    else return 'more-context'         /* Parse here will fail */
```

We can also make partial solutions returning 'failure' in stead of 'more-context'. For this, we look for certain restrictions for the whole grammar, and check whether the

given Text part can fulfil them. Test 3 can be transformed in such a test by making a regular expression that accepts all substrings of G. We will not work this out.

Idea 4

This idea uses some knowledge about the order of terminals in the grammar. Such a restriction for the whole grammar appears in the following example:
Grammar: $S ::= a\,S\,b \mid c$

In this grammar, we will never find an 'a' after a 'c'. In this case, we could write $a \leq c$. A precise definition of $\leq$:

$$S \leq T \;\Leftrightarrow\; \alpha\,S\,\beta\,T\,\gamma \in L(G)$$

The test we can make with this relation:

```
Test_Order (Text, Symbol)
     X_1 .. X_n := Text
     if there are X_p and X_q with p<q and not X_p ≤ X_q
     then return 'failure'
     else return nil fi
```

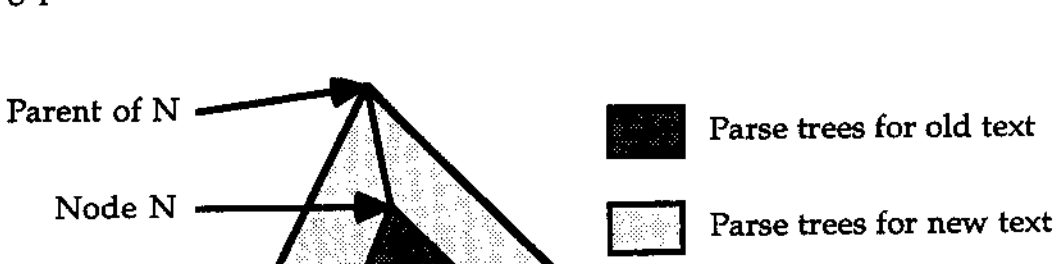
Conclusions

All the given tests without parsing are partial, and this is not surprising, since we showed that the test is at least as hard as parsing. If there is a partial solution that works good enough in practice, then this is an attractive way to solve the CheckForTree in this way. But we have no performance indications for these tests, so we can draw no conclusions about practical performance of these tests.

4 Bidirectional recognising

Introduction

Although we have no performance tests, We don't expect the partial solutions of chapter 3 to be good enough in practice. And after all, we still need to parse when we found the right node. We saw in the CheckForTree' algorithm that a slightly adapted substring parser can decide the CheckForTree algorithm by itself. The problem with this solution is that the text that has to be parsed after going to the parent node (in inc_parse of chapter 2) will always include the text that we already parsed, but the substring parser can not reuse the work it has done. In a picture, the situation looks like (a).



(a)

In essence the substring parses does work for all parse trees in which the old text can fit. So in fact, the work we will encounter in building the bigger parse tree has already been done. So why not reuse it? If we do so, we have an island parser. We will adapt Earley's parser for island parsing, unlike the substring parser, which adapts Tomita's parser.

A short description of Earley's recogniser

We will describe Earley's recogniser ([E70]) in short. Although a recogniser does not return parse trees, it is not hard to change it into a parser. Earley's recogniser tells whether the string $S_1 .. S_n$ is in L(G). We are not interested in lookahead, so we remove this from Earley's algorithm. To explain his parser, we need a few definitions:

A **dotted rule** is a rule of the grammar, with a dot (•) placed in it. So if N ::= a b c is a rule, then N ::= a b • c is a dotted rule. The • indicates where we are with recognising that rule.

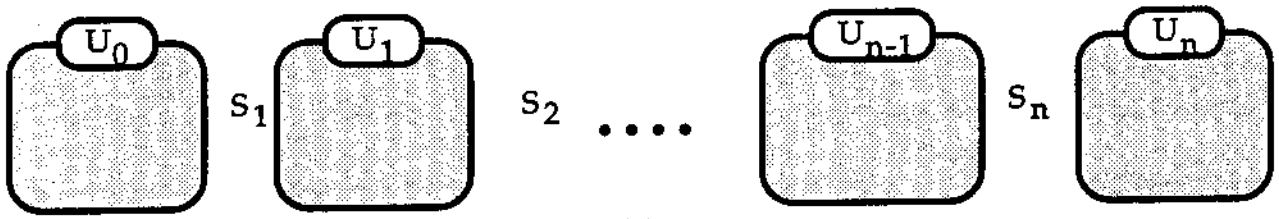
An **item** is a tuple containing a dotted rule and a number StartPos, with $0 \le StartPos \le n$ (n is the length of the input string). StartPos denotes where the recognition according to this rule started. An **item set** U_k, with $0 \le k \le n$, is a set containing items. Only items that are in some way 'useful' according to input symbols $S_1 .. S_k$ are placed in U_k. More precise:

$$\text{An item } \langle N ::= \alpha \bullet \beta, i \rangle \text{ is in } U_k$$

$$\Leftrightarrow$$

$$\exists \text{nonterminal } M : M \Rightarrow^* \pi\, N\, \theta \ \wedge\ \pi \Rightarrow^* S_1 .. S_i \ \wedge\ \alpha \Rightarrow^* S_{i+1} .. S_k$$

In a picture, the item sets are placed as follows around the input symbols (b):



(b)

Initially, we place all items <N::=•α,0> in item set U_0, where N::=α is a grammar rule. This represents that we can recognise the first 0 (zero) input symbols using rule N::=α. The 0 in the tuple indicates that we started trying this rule in set U_0. After this initial step, the sets are filled further using one of the following actions:

```
Scanner: /* continue parsing if next input symbol is ok */
     if <N ::= α•Sk+1β,StartPos> in Uk
     then add <N ::= αSk+1•β,StartPos> to Uk+1 fi

Predictor: /* adds items that can produce needed nonterminals */
     if <M ::= α•Nβ,StartPos> in Uk
     with N nonterminal and N ::= σ in G for some σ
     then add <N ::= •σ,k> to Uk fi

Completer: /* 'Scans' other items after a nonterminal is produced */
     if <M ::= α•Nβ,StartPos> in Uk
     and <N ::= σ•,k> in Um
     then add <M ::= αN•β,StartPos> to Um fi
```

Adapting Earley for symmetry

The first step towards **bidirectional recognising** (recognising in the normal left-to-right way and in the reverse way) is to remove the left-to-right bias from Earley's algorithm. The left-to-right bias appears in the StartPos in the item tuple. We will replace it by the left and right 'immediate neighbour items' of the state. So our item is a triple containing a dotted rule, a set of left neighbour items and a set of right neighbour items. The left neighbours are items having a dotted rule with the • moved one symbol to the left, and the right neighbours have the • moved one symbol to the right.

But written in this way, there seems to be double storage of this data: an item A has neighbour B, and B has neighbour A. It seems more convenient to think about a relation between A and B. We express this relation by a **link**. A link is a tuple <Left,Right>, where Left is an item in an item set, and Right is another item with the • in its dotted rule moved one symbol to the right. In a picture, links look like (c).

(c)

If there is a link with 'left'=A and 'right'=B, we say that there is a link between A and B. We also write A ↠ B. If A↠ ... ⇒B (or A=B), we write A ⇒* B.

A link is an explicit reflection of Earley's Completer action: when we found a production for a useful nonterminal, we trigger a completer action. Earley does not make links, but just adds new items, if it finds old items that need the nonterminal. We also make a link from the old to these new items.

Furthermore, we make shift possibilities. A **shift possibility** is a triple $<S,U_m,U_n>$. S is some symbol, U_m and U_n are itemsets. A shift possibility indicates that symbol S has been recognised, using the input symbols $S_{m+1} .. S_n$. Usually, S will be a nonterminal, but this definition allows us to make shift possibilities for terminals. Formally: $<S,U_m,U_n>$ is a shift possibility $\Rightarrow$ $(S \Rightarrow^* S_{m+1} .. S_n)$.

We define the following properties of items:

We call an item **left-complete** ⇔ its dotted rule is of the form S ::= • α.

We call an item **right-complete** ⇔ its dotted rule is of the form S :: = α •.

We call Item **complete** ⇔

∃Item' : (Item ⇒* Item' and Item' is right-complete) and

∃Item" : (Item" ↠* Item and Item" is left-complete)

Intuitively, an item is complete if it is between some left- and right-complete item.

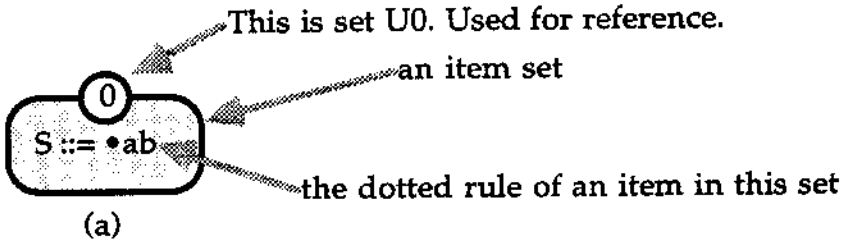
Recognising with these notions

We will first give some examples, to show how these notions can be used to make a recogniser.

Grammar: S ::= a b

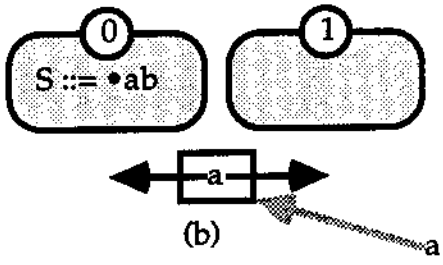
Input string: a b

We start with an initial itemset that is located before the 'a' symbol of the input. We want to try to recognise S, so the dot is placed at the left of the production rule. This looks like (a). To save space, we remove the spaces that separate the terminals from the production rules. In our example, this gives no problems, since all symbols consist of only one character.



(a)

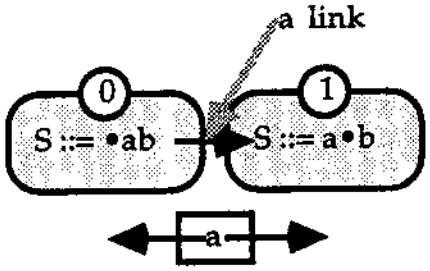
Now, we want to process the 'a' of the input string. Therefore, we make a new, empty item set and a shift possibility that indicates that an 'a' has been 'recognised':



(b)

a shift possibility for 'a' between 0 and 1.

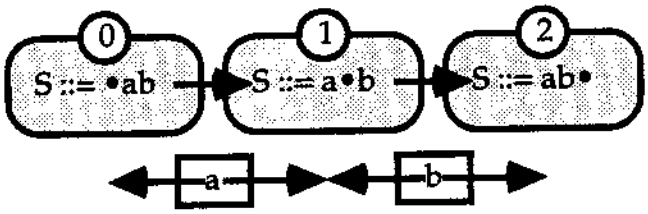
The S::=•ab item can use this shift possibility, since the left side of the shift possibility points at the set the item is in, and the item just needed to shift an 'a', which is made possible by the shift possibility. So the item shifts its 'a', and makes an item and a link to it in set 1, the other end of the shift possibility. The result is (c).



(c)

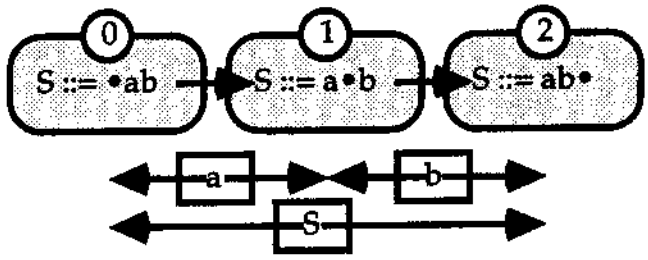
As we can see, a link is a kind of reflection of an existing shift possibility. So it is not necessary to make the links explicit. Instead, we can refer to that shift possibility. But we will draw the link in our pictures, because it makes the situation more clear than a reference to a shift possibility.

Next, we want to process the 'b' of the input string. So we make a new item set and a new shift possibility for the 'b'. The S::=a•b item in set 1 uses this shift, resulting in a new link and a new item in the new set. The situation now looks like (d).



(d)

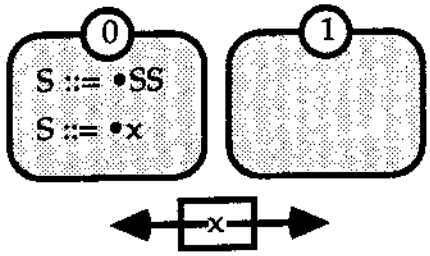
The S::=ab• item is complete (it is right-complete and S::=•ab⇒S::=a•b⇒S::=ab•). This means that the S nonterminal has been recognised. Therefore, a new shift possibility for S between set 0 and set 2 is added. The situation now looks like (e). The creation of this shift possibility does not trigger any further actions, since there are no items having the • before an S in set 0.



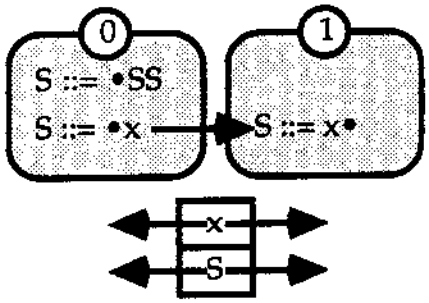
(e)

The input sentence 'ab' has been recognised, because we found a shift possibility between the leftmost itemset (0) and the rightmost itemset (2). The top nonterminal of the tree we found is S.

Now we will look at an ambiguous grammar.
Grammar: S ::= x | S S
Input string: x x x
We place both rules with the dot at the left in the initial set, and we make a shift possibility for x between set 0 and 1. The situation looks like (a).

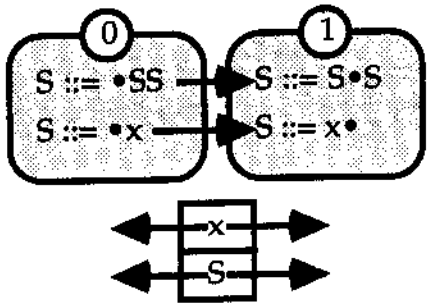


(a)

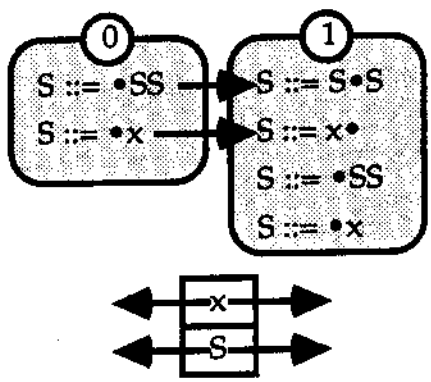


(b)

The S::=•x item can use this shift possibility, and makes a new link and item in set 1. This item is complete, so a new shift possibility for S between 0 and 1 is made. The situation is like (b). This new shift possibility is be used by S::=•SS. A new item and link is made (c).



(c)

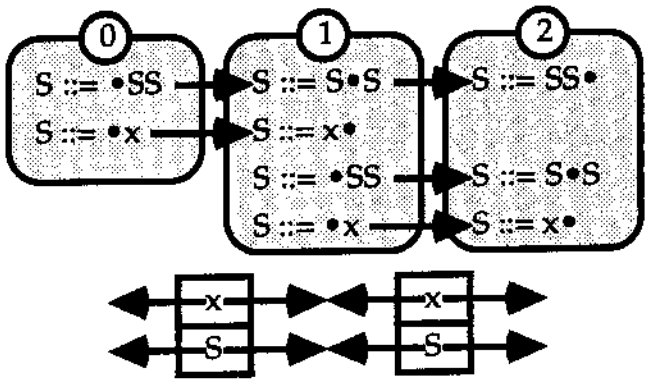


(d)

Something more has to be done. The S::=S•S item tries to shift an S, but there are no production rules for S with a • at the left in set 1, so there will never be a shift

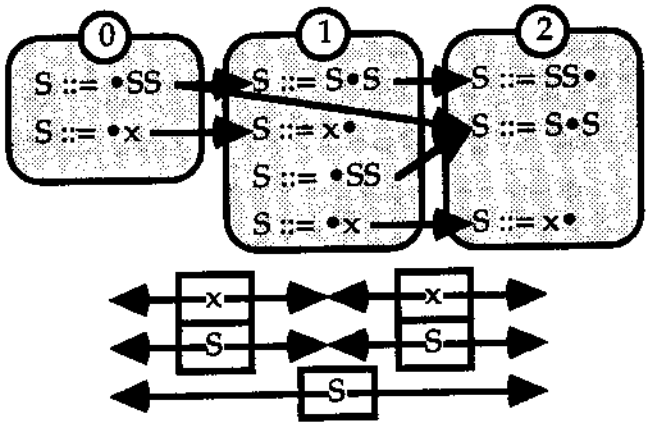
possibility with the left side at this set, if we do nothing. So a predictor action like in Earley's algorithm is needed. In fact, nothing is predicted, but we simply put all the rules that can recognise an S with the dot at the left in set 1. The situation now looks like (d), and nothing more can be done.

Next, we process the second x of the input string. We add another shift possibility for x, between set 1 and set 2. The S::=•x item can use it, and makes an S::=x• item in 2. Because S::=x• is complete, a shift possibility for S between 1 and 2 is made. Both the S::=•SS and the S::=S•S item can use it, resulting in two new items and links (e).



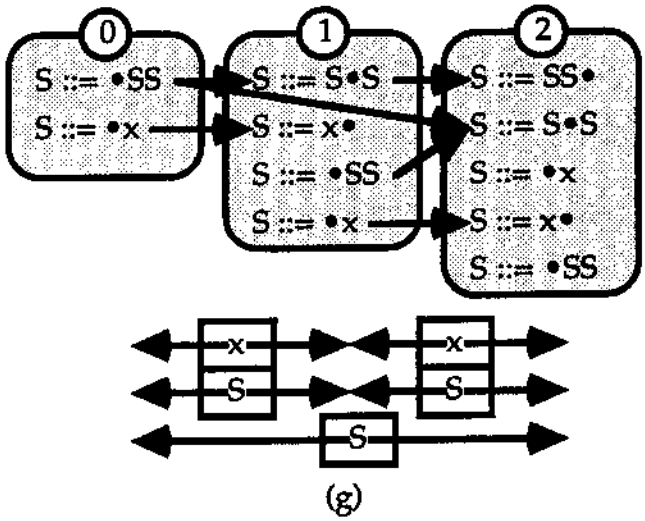
(e)

The S::=SS• item is complete, so a new shift possibility is made between 0 and 2. The S::=•SS item in 0 can use it, resulting in a new link to the S::=S•S item in set 2. The item already exists, so no new item has to be made (f).



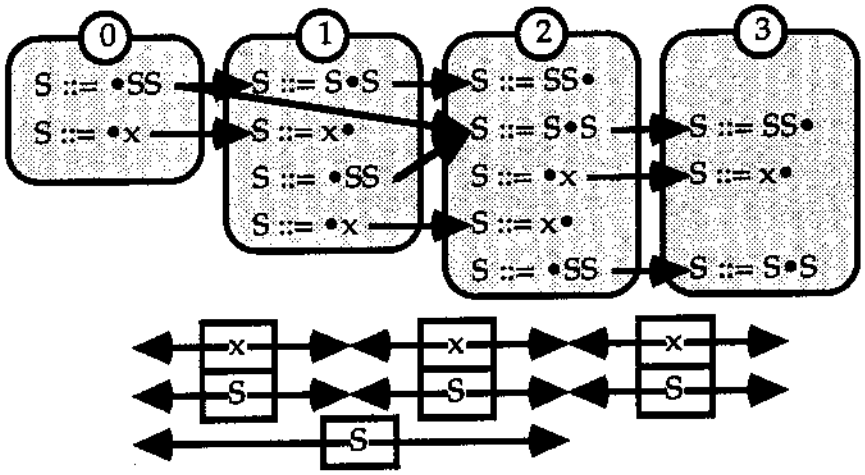
(f)

Again, a predictor step is needed, because the S::=S•S item tries to recognise an S. Therefore, the items S::=•x and S::=•SS are added to set 2 (g).



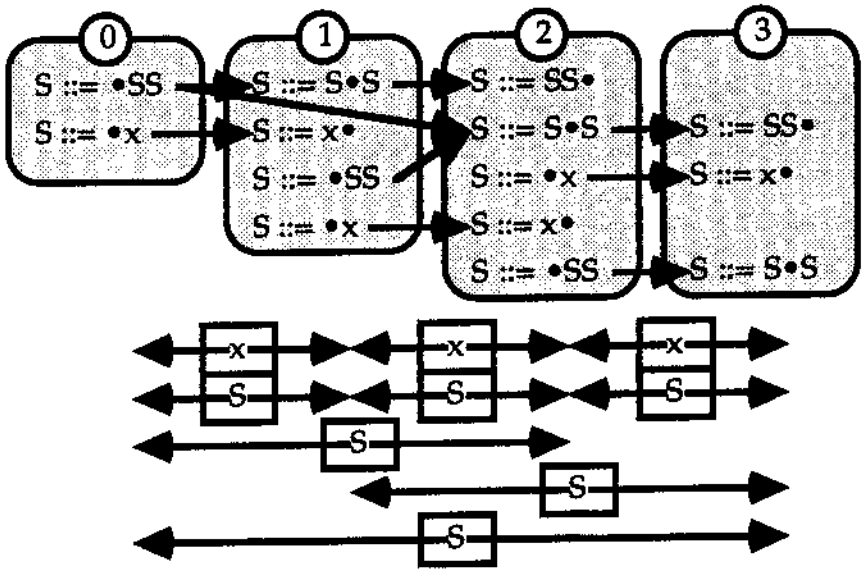
(g)

Now, we are ready to process the last x of the input string. We make a new shift possibility for x. The S::=•x makes a new link and item. The item is complete, so a new shift possibility for S between sets 2 and 3 is made. Items S::=•SS and S::=S•S use that shift possibility. They make new items S::=S•S and S::=SS• (h).



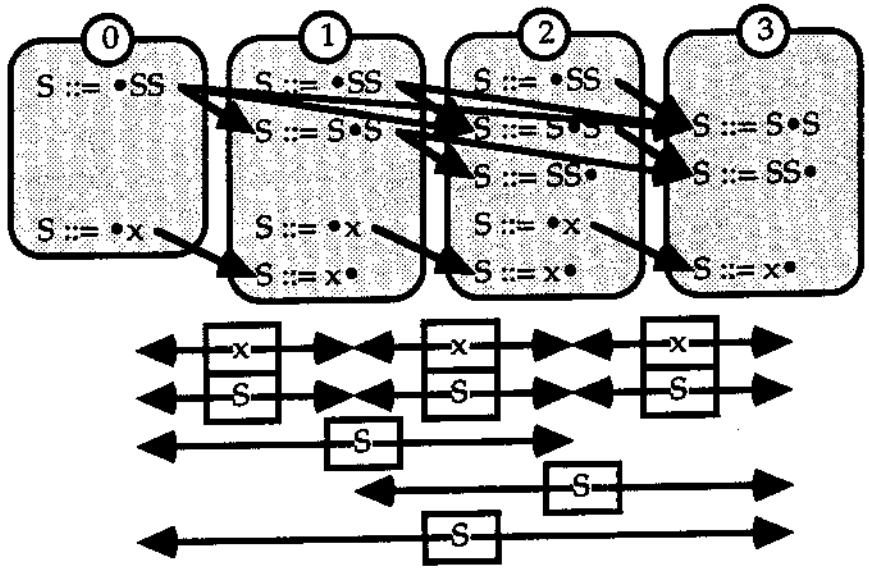
(h)

The item S::=SS• is complete, in two ways. First, because it is linked to S::=•SS in set 1. This results in a shift possibility for S between 1 and 3. Second, because it is linked to S::=•SS in set 0. This results in a shift possibility for S between 0 and 3 (i).



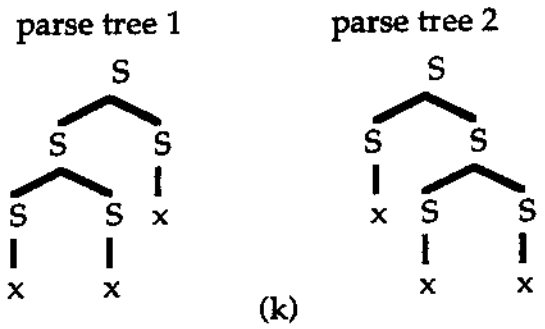
(i)

The shift possibility between 0 and 3 is used by S::=•SS, resulting in a link to item S::=S•S in 3. The shift possibility between 1 and 3 is used by 2 items in set 1: S::=•SS makes a link to S::=S•S in 3. S::=S•S makes a link to S::=SS• in 3 (j).



(j)

The item S::=SS• in set 3 now has another way to be complete: by following the link to S::=S•S in 1, and then back to S::=•SS in 0. But this gives a shift possibility between 0 and 3, which already exists. This double way to make a shift possibility exactly represents the ambiguity in our grammar, Now, we have processed all input symbols, and we found a shift possibility for S between the leftmost and the rightmost set. This means that we recognised the input string. The two parse trees representing the input are (k):



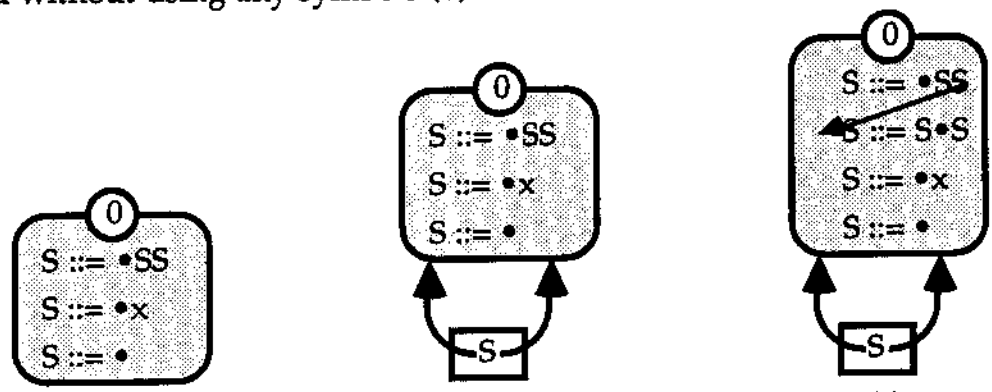
(k)

Finally, we will look at an example with an empty production.

Grammar: S::=x | S S | ε

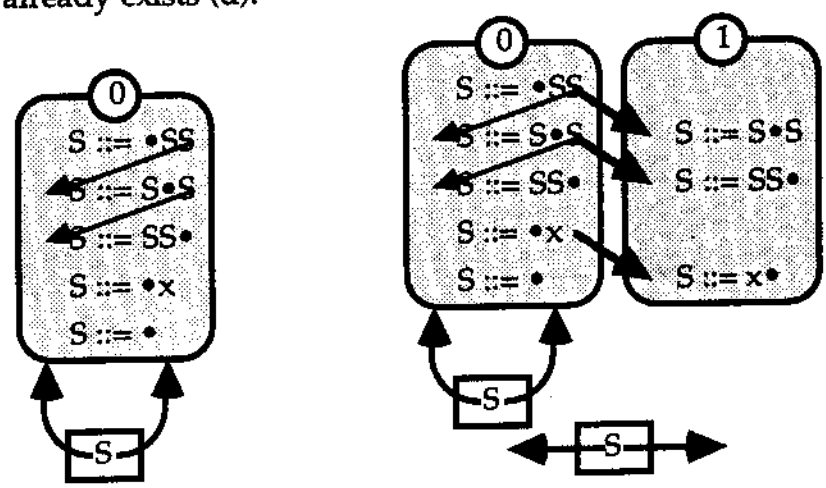
Input string: x

Again, we start with placing all rules with a dot at the left in a set (a). The S::=• item is complete, so a shift possibility between 0 and 0 is made, indicating that an S was recognised without using any symbols (b).



(a) (b) (c)

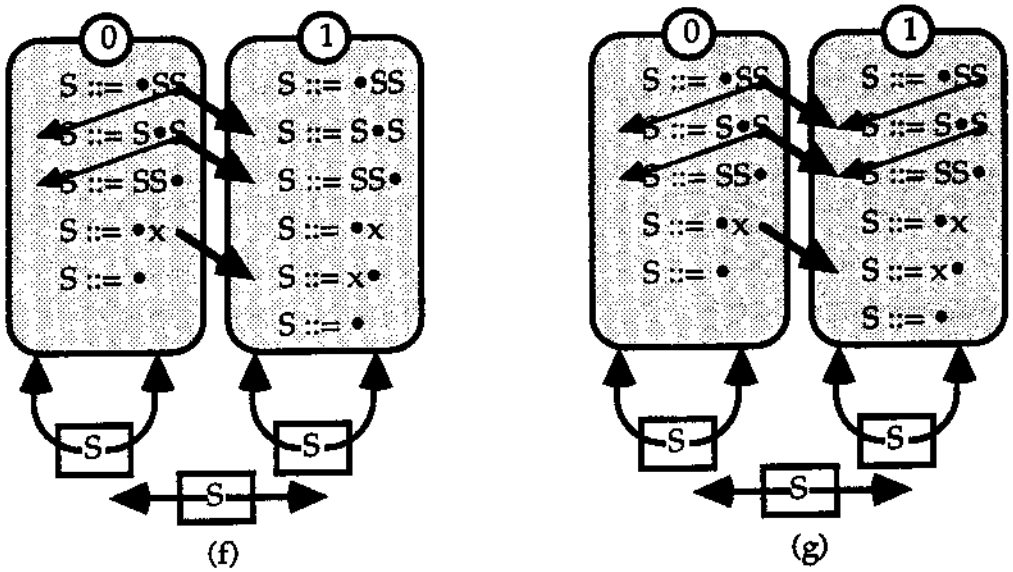
The S::=•SS item uses this shift possibility. The situation now looks like (c) (We made the link somewhat thinner in the picture, otherwise the new item would be unreadable). The S::=S•S item can do its shift directly after it is added. It adds an S::=SS• to the set. Although this item is complete, nothing is done, since the resulting shift possibility already exists (d).



(d) (e)

We are ready to process the 'x' of the input string. We add a shift possibility for x between 0 and 1. The S::=•x item uses it. It is complete, and a shift possibility for S between 0 and 1 is made. The S::=•SS and S::=S•S in 0 use this shift possibility, and also make a link to set 1 (e). The S::=SS• is complete, but the shift possibility already exists, so nothing happens.

Because the S::=S•S item tries to shift an S, we add all rules that can produce an S to set 1. Because item S::=• is added, a shift possibility for S between 1 and 1 (f) is added.



The items S::=•SS and S::=S•S were waiting for this, and new links are made (g). The S::=SS• in set 1 now is complete in 2 new ways, but both shift possibilities already exist. The x has been recognised, since we found an S shift possibility between 0 and 1.

An algorithm for Left to Right recognising

In this section, we give a more formal description of the parsing method illustrated in the previous sections. In the algorithms, S is a symbol, N a nonterminal.

```
recognise (X1 .. Xn,G)
     for k = 0 to n do Uk := ∅ od
     for each N ::= α in G do add(N ::= •α,U0) od
     for k = 1 to n do
          make shiftposs between Uk-1 and Uk for Xk
          while an action is possible do action od
     od
     if there is a shiftposs between U0 and Uk
     then return 'accept' else return 'reject' fi
```

The possible actions are as follows. Note that the scanner only makes moving the • to the right possible. The predictor only predicts to the right. This still is a kind of left-to-right bias.

```
scanner /* makes new items and links */
     if there is some set Uk containing an Item N ::= α•Sβ
     and there is some k≤m≤n /* n=#input symbols */
     and is a shift possibility for S between Uk and Um
     then
          Item' := add(N ::= αS•β,Um)
          make a link from Item to Item'
     fi

completer /* makes new shift possibilities */
     if Item with dotted rule N ::= •α in some set A
     and Item' with dotted rule N ::= α• in some set B
     and Item ⇒* Item' then
          make new shift possibility for N between A and B
     fi

predictor /* adds items that produce needed nonterminals */
     if Item with dotted rule M ::= α•Nβ in some set A
     and N::=γ is production of G
     then add Item' with dotted rule N ::= •γ to A fi

add (N=α•β,Set)      /* find the item with this dotted rule */
     Item := find an item with dotted rule N ::= α•β in Set
     if Item not found
     then add Item without links with dotted rule N ::= α•β to Set
     fi
     return Item
```

Comparison with Earley's algorithm

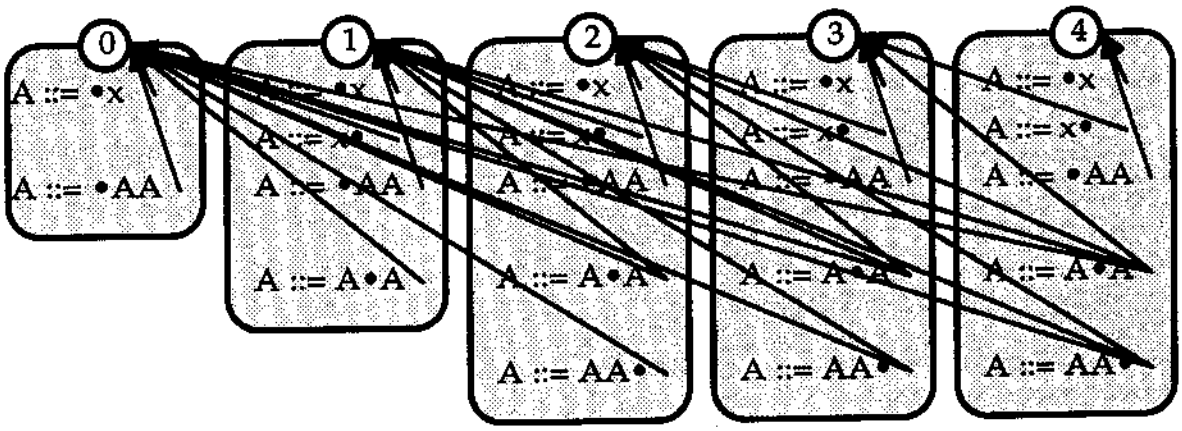
In this section, we will compare Earley's algorithm and our left-to-right algorithm. First we look at an example.

Grammar: A ::= x | A A
Input string: x x x x

If we follow Earley's algorithm, the result is this table ([E70] p.99). We removed look-ahead data and end-of-input markers, and adapted it to our notation.

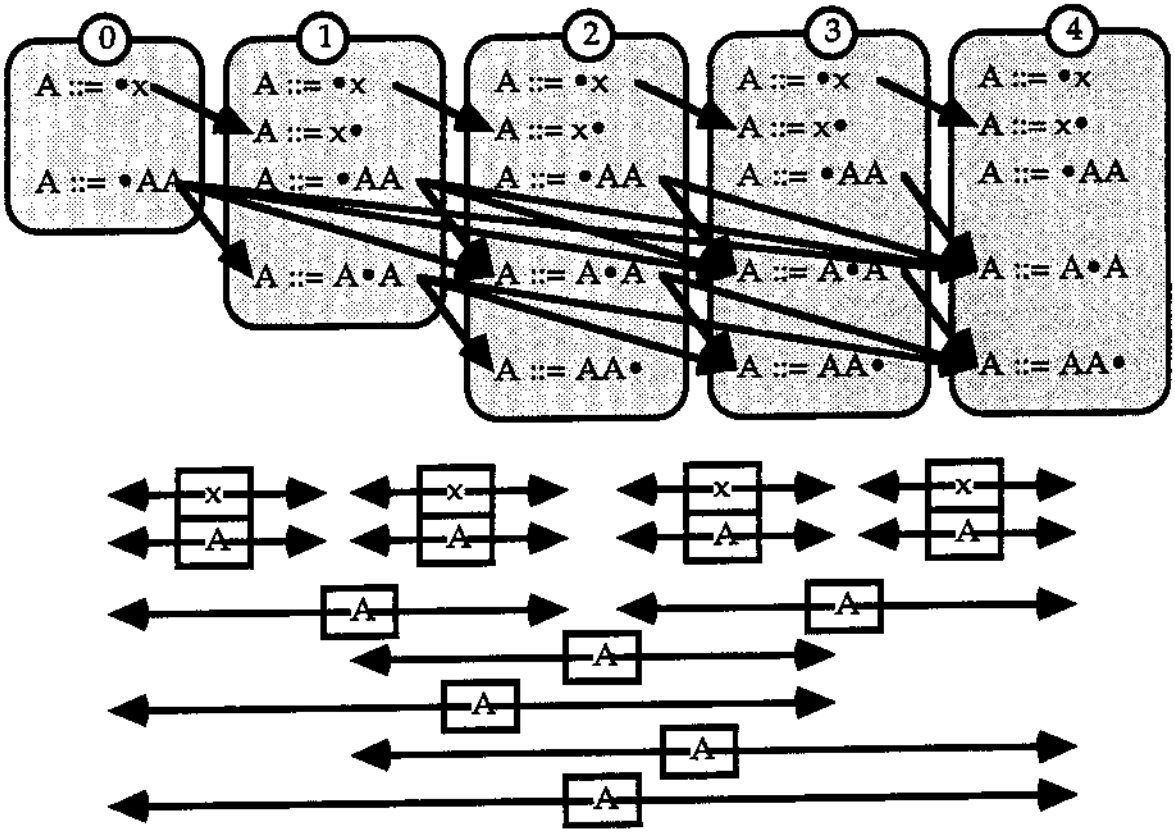
Item set	Dotted rule	StartPos	Item set	Dotted rule	StartPos
			U_3	A ::= x•	2
U_0	A ::= •x	0		A ::= AA•	1
	A ::= •AA	0		A ::= AA•	0
				A ::= A•A	2
U_1	A ::=x•	0		A ::=A•A	1
	A ::= A•A	0		A ::= A•A	0
	A ::= •x	1		A ::= •x	3
	A ::= •AA	1		A ::= •AA	3
U_2	A ::= x•	1	U_4	A ::= x•	3
	A ::= AA•	0		A ::= AA•	2
	A ::= A•A	1		A ::= AA•	1
	A ::= A•A	0		A ::= AA•	0
	A ::= x•	2		A ::= A•A	3
	A ::= •AA	2		A ::= A•A	2
				A ::= A•A	1
				A ::= A•A	0
				A ::= •x	4
				A ::= •AA	4

We want to compare these sets with our pictures. Therefore, we put the items that are produced by Earley's algorithm in a picture, and make links with arrows. The result is (a).



(a)

If the same grammar and input string is provided to our algorithm, we get picture (b).



(b)

As illustrated by these pictures, we notice the following similarities and differences:

similarities

- Both use dotted rules.
- Both have a set between each two input symbols.
- Each dotted rule can occur at most one time in a set between two input tokens.
- The invariant[1] is the same for the items[2]. This can be seen in the pictures because the sets in Earley's and our recogniser contain states with exactly the same dotted rules.
- We have similar actions as in Earley:
  'scanner' handles the shift of some symbols.
  'predictor' does exactly the same.
  'completer' works out similar

differences

- Our scanner handles all shifts, Earley's scanner handles only terminal shifts.
- We have an explicit notation for recognised nonterminals: the shift possibilities. In Earley, this is not the case.
- We do not have a look-ahead possibility.
- We have links between two items, Earley has links between an item and a set.
- Perhaps the most important difference is that our recogniser is symmetric for L-R and R-L recognising.

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[1] The invariant was given at the beginning of this chapter.

[2] This only holds for the left-to-right version of our parser without removing of useless items.

Discussion of the symmetry difference

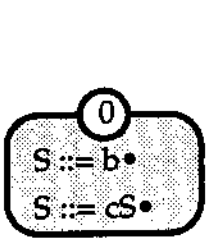
Earley's algorithm gives troubles if we try to reverse the parse direction. This is caused by the way the links are made. In Earley, a link is maintained to the set containing the 'left-complete' (in our terminology) item. This works perfect if only is parsed from left to right, since an item is always left-complete in that case. However, in the island parser of our final goal, we need to start somewhere in the middle of recognising an item, resulting in items with only a temporary left-complete item. In this case, it gives problems to link to a left-complete item. In our recogniser, an item maintains links to immediate neighbours of it. Because of this, a recognise action is more complicated and will cost more. We will look at a possible solution for this problem in chapter 7, and work it out in chapter 8.

Example of Right to Left recognising

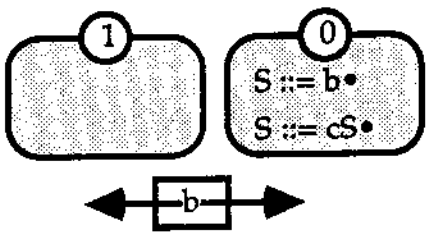
Because right-to-left recognising is symmetric to left to right recognising, we limit ourselves to an example of right to left recognising.

Grammar: S ::= b | cS
Input string: cb

Just as in the case of left to right recognising, we start by placing all rules in a set, with the dot at the start. In right to left parsing, this means placing the dot at the right (a). To process the first (the rightmost in right to left recognising!) symbol, we make a new shift possibility for b between 0 and a new set 1. Note that this set is left of the old set! (b). Also note that our numbering gets a little inconsistent, but that is no real problem.

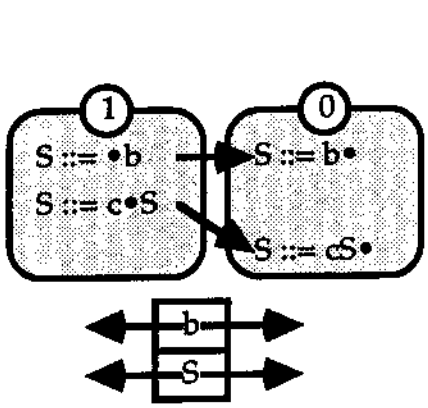


(a)

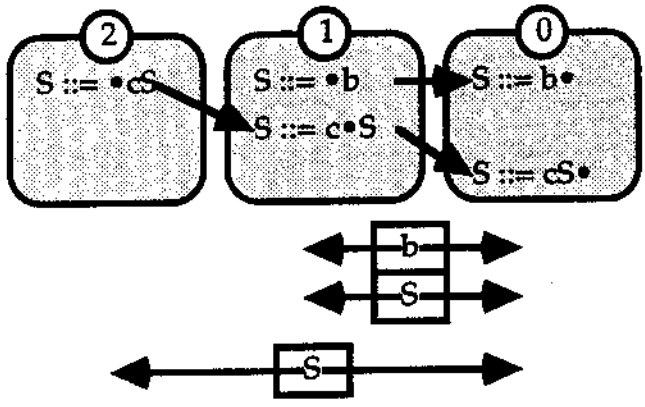


(b)

The S::=b• item can use the shift, and places an S::=•b item in 1. That item is complete, and it adds an S shift possibility between 0 and 1. The S::=cS• item uses that shift, resulting in an S::=c•S item in 1 (c). The predictor does nothing, because there is no nonterminal at the left of the •.

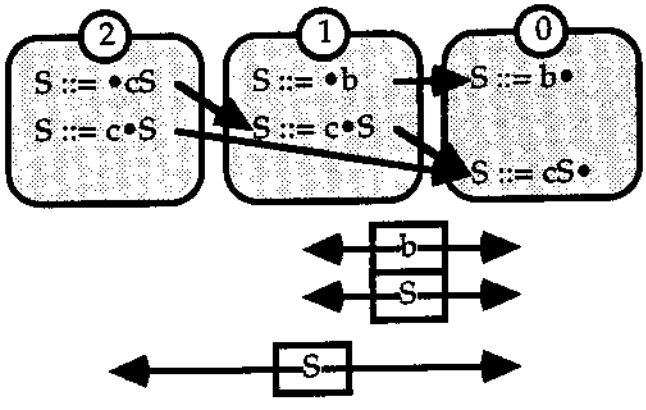


(c)



(d)

Next, we add a shift possibility for the first 'c' (when reading from right to left) between 1 and 2. The S::=c•S uses it, and makes an item S::=•cS in 2. This item is complete, so a new shift possibility for S between 2 and 0 is made (d). The S::=cS• item in 0 uses it, and makes an item S::=c•S in 2 (e).



(e)

We expect that the reader now understands the symmetry in our parsing methods.

5 Island Parsing

This chapter consists of two parts. First, we will make an island recogniser. Then, we will turn this island recogniser into an island parser.

I: Adapting the bidirectional recogniser for island recognising

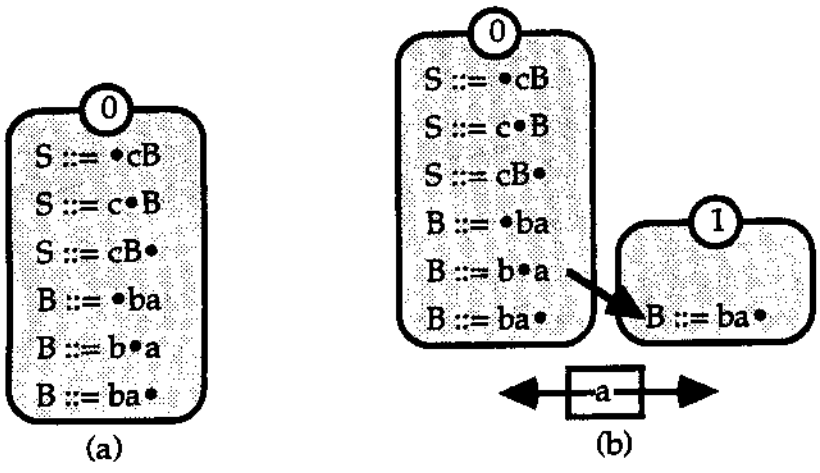
The context idea

The basis idea for island recognising is simple: since the data structures look the same for both directions, we simply parse in the direction we need. But there is a problem when we want to turn the direction: initially, we placed all rules with the dot at the *start* in an initial set, indicating that we want to recognise these rules. But what is the start side when we may change the direction? In fact, the 'initial' item set may end up somewhere in the middle of the input string, when we allow turning the direction.

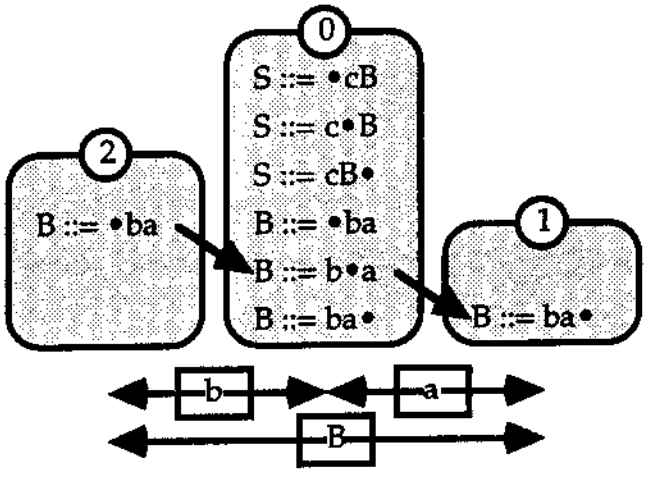
The solution is to put the dot at any place in any production rule. The items that are needed certainly exist in this case. But this does not solve all the problems. We are going to give some examples to show that we need some notation for unknown context. Look at the following example:

Grammar:
B ::= b a
S ::= c B
input string:
first an 'a' at the right, and then 'c b' at the left

As said, we put the production rules with the dot at any place in the initial itemset (a). Now, we make a shift possibility for the 'c', at the right side. The item B::=a•b uses it, and makes a new item B::=ab• in set 1. This item is not complete, so we are ready (b).

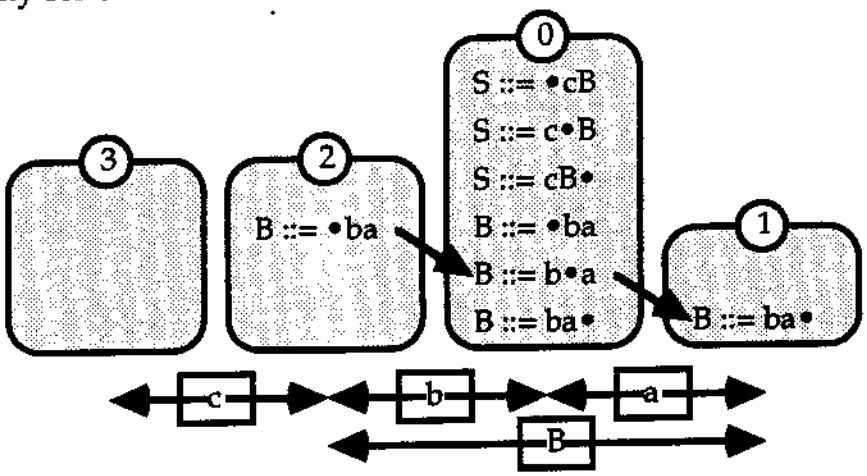


Next, we make a shift possibility for 'b', but now on the left side. The B::=b•a can use it, is complete and makes a shift possibility (c).



(c)

As a last step, a shift possibility for 'c' is made (d). But no action is possible! We expect a shift possibility for S between 3 and 1.



(d)

The problem is caused by the absence of an S::=cB• item in set 1. That item was not added, because the B::=ba• was found to be right-complete, but not left-complete. The B::=•ba was located somewhere in an unknown context at that time (b).

As shown, some sets contain too much items (set 0, e.g. the B::=•ba is useless, since it will never be able to shift the 'b') and others too little (set 1, where we missed an S::=cB• item). We will show how the situation of a set containing too little items can be avoided, by means of a context set.

Another interesting point to use a context is to decide between 'failure'and 'more-context' (chapter 2). Consider the following example:

Grammar:

S ::= A | B

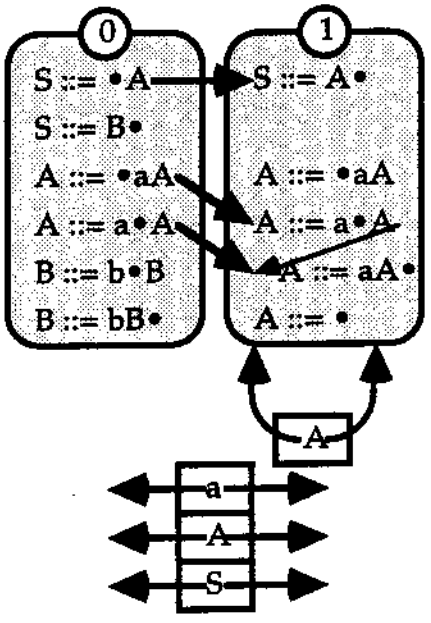
A ::= a A | ε

B ::= b B | ε

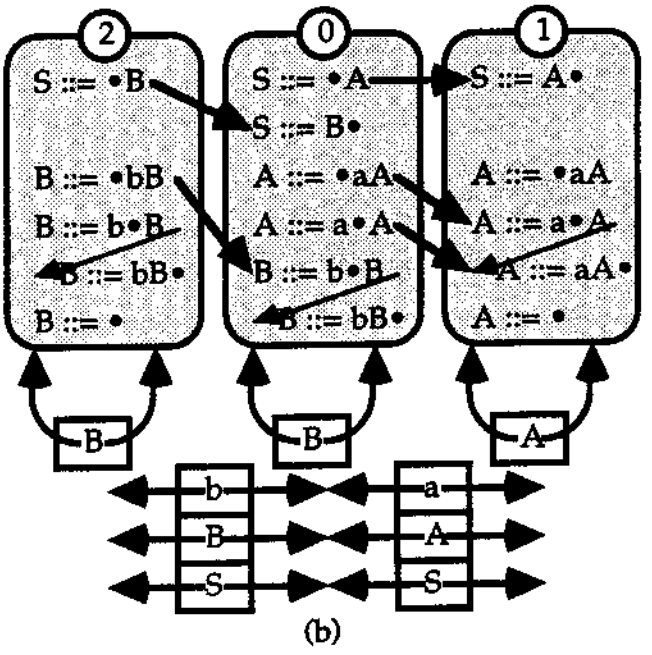
Input:

'a' at the right, then 'b' at the left (note that 'b a' is no string in L(G))

After all dotted rules are placed in 0, and a shift possibility for 'a' to set 1 is made, the situation looks like (a) (only items and shift possibilities that are of interest for us to show the point are shown).



(a)



(b)

We make a shift possibility for 'b', between 0 and 2. Now, the situation looks like (b). Since we found no shift possibility between 1 and 2, we know that we did not recognise the input. But what can we say about usefulness to continue parsing[1], by only looking at this picture? We think that the best solution is to place something representing *any possible* left context at the left of set 2, and something representing any right context at right of 1. If it is possible to create at least one shift possibility using the left or right context, we know that it still is possible to recognise the input (the 'more-context' case), otherwise we can safely return 'failure'.

We make an object representing any possible context as follows: we place items with all possible dotted rules in a set. This represents that each possible dotted rule can be reached with an appropriate input. Next, we make a shift possibility for *?* between that set and itself, and do all possible actions to get the appropriate links. The *?* is a symbol that matches any other symbol. This shift possibility represents that it is possible to recognise any symbol in the context[2].

Grammar:

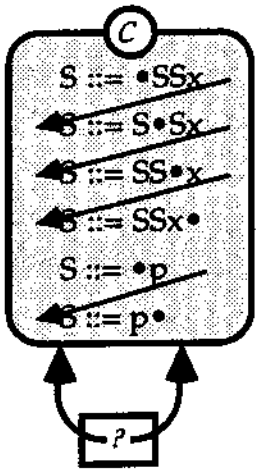
S ::= S S x | p

---

[1] The question whether we should return 'more-context' or 'failure', see chapter 2

[2] We assume that all nonterminals can produce some terminal-only string. If this is not the case, a *T* shift possibility (next section) in stead of an *S* shift possibility can be used.

The context set now looks like (c). Note that no additional shift possibilities for S are made, although they are complete. This is because we already have a $\mathcal{T}$ shift possibility.



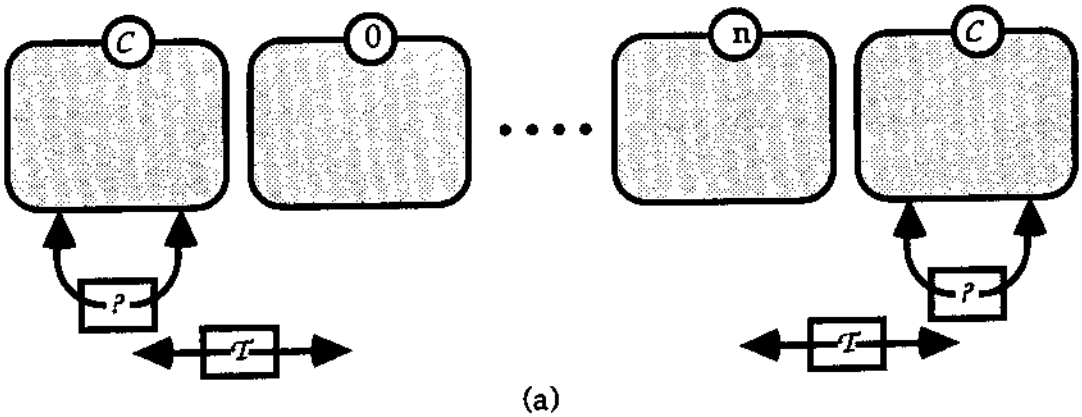
(c)

Using a context set

In this section, we will illustrate the use of a context set. If we are working from left to right, we only need a left context, because we are in a situation very similar to Earley without lookahead: items are added without knowledge about the rest of the symbols that are going to be parsed. For the same reason, we only need a right context if we parse from right to left.

Because of this, we need to swap the context set to the other side, if we want to change the parse direction. This is one of the reasons to keep a separate context set, and not just change the outermost sets into context sets.

So the intention is that the context can only be reached by shifting at least one unknown input symbol. We enforce this by making a shift possibility for $\mathcal{T}$ from the outermost sets to a context set. The $\mathcal{T}$ matches with any terminal, but not with nonterminals. Working this way, shift possibilities to the context are made explicit, which is just what we needed. The situation is shown in (a).



(a)

While parsing, we use only one context. But when we need to decide about failure (chapter 2), we need a context at both sides. We will look at this after the following example of left to right parsing using a context.

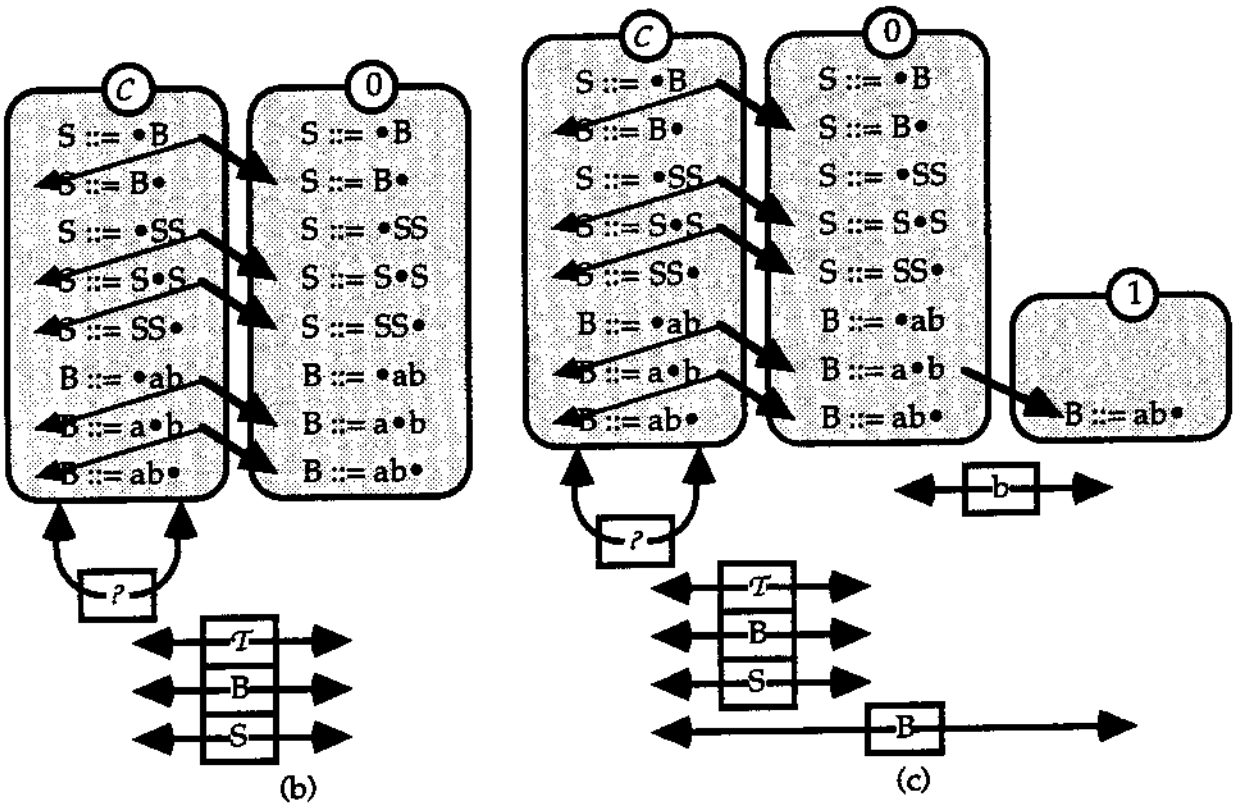
Grammar:

S ::= B | S S

B ::= a b

Input string: b a b

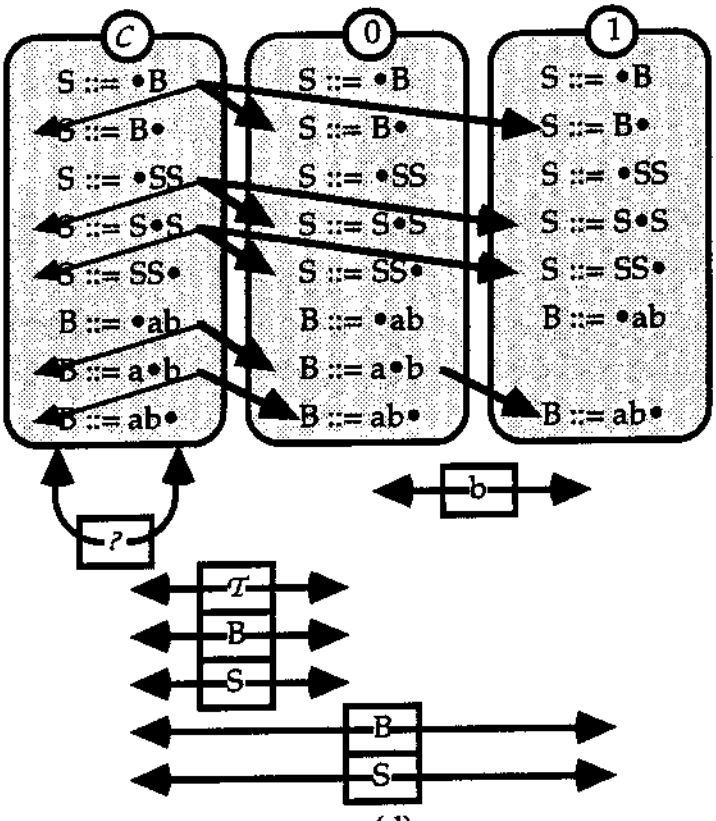
Now, we start with a situation like (b). Note that both B::=•ab and B::=a•b can shift their terminal, since both matches with the $\mathcal{T}$ shift possibility. We have not added the right context, since we want to parse to the right. The B shift possibility was made because the B::=ab• item in 0 is complete with appropriate left context. Because of this shift possibility, The S::=B• is also complete, causing an S shift possibility.



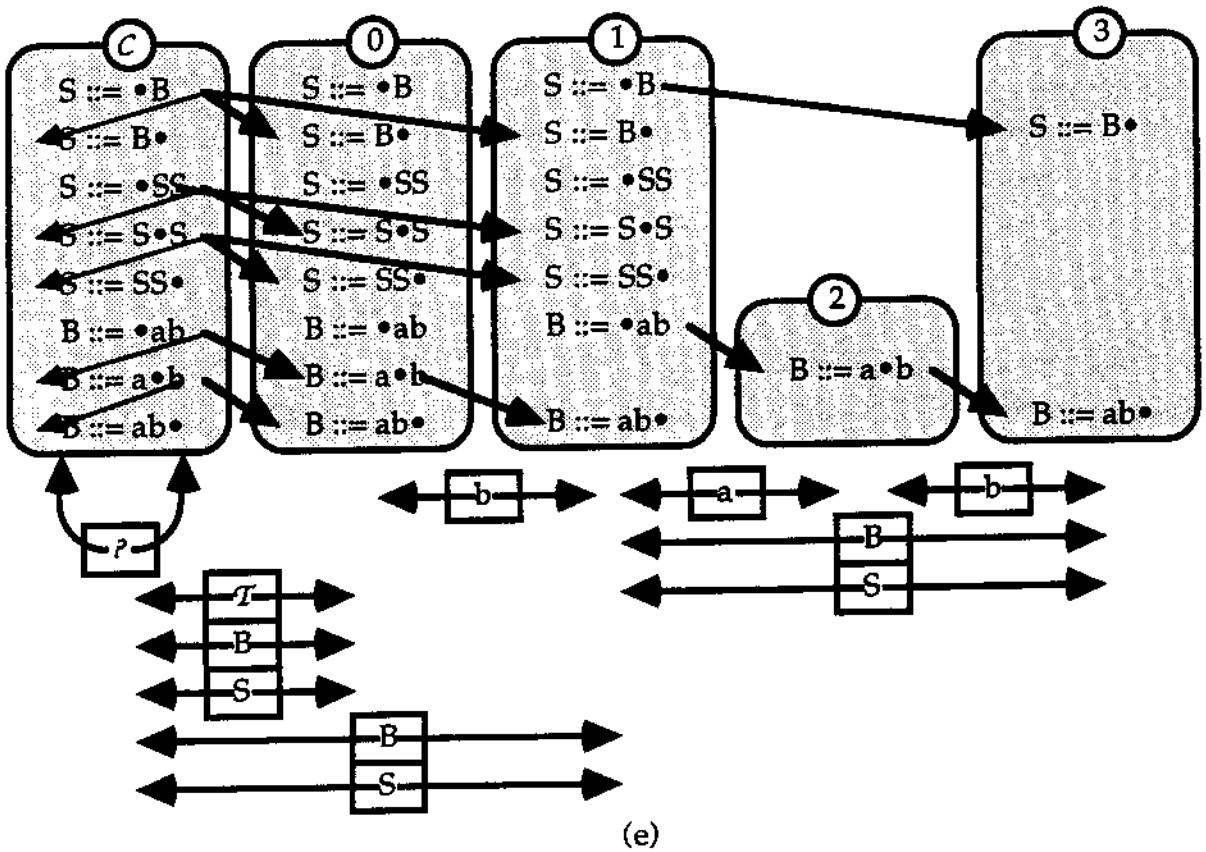
We start parsing by adding a shift possibility for b between 0 and 1. Item B::=a•b can use it, and makes B::=ab• in 1. This item is complete because it is linked to B::=•ab in *C*. Note that this was not true if we did not have a context, in that case nothing would happen. So a shift possibility between *C* and 1 for B is made (c).

The S::=•B in *C* can use this shift possibility, and makes an S::=B• in 1. This item is also complete, so a shift possibility for S between *C* and 1 is made. This shift possibility is used by S::=•SS and S::=S•S in *C*. Finally, the predictor adds items S::=•B, S::=•SS and B::=•ab to set 1 (d).

At this point, we can see that only the b gives no complete parse tree, since there is no shift possibility between 0 and 1. We can also see that an appropriate left context can give both a tree with B and a tree with S at the top. Now, we process the rest of the input string. First we make a shift possibility for 'a' between 1 and 2. Only B::=•ab uses it, and it only makes B::=a•b in 2.


C
S ::= •B
B ::= B•
S ::= •SS
B ::= S•S
B ::= SS•
B ::= •ab
B ::= a•b
B ::= ab•
0
S ::= •B
S ::= B•
S ::= •SS
S ::= S•S
S ::= SS•
B ::= •ab
B ::= a•b
B ::= ab•
1
S ::= •B
S ::= B•
S ::= •SS
S ::= S•S
S ::= SS•
B ::= •ab
B ::= ab•
b
?
T
B
S
B
S

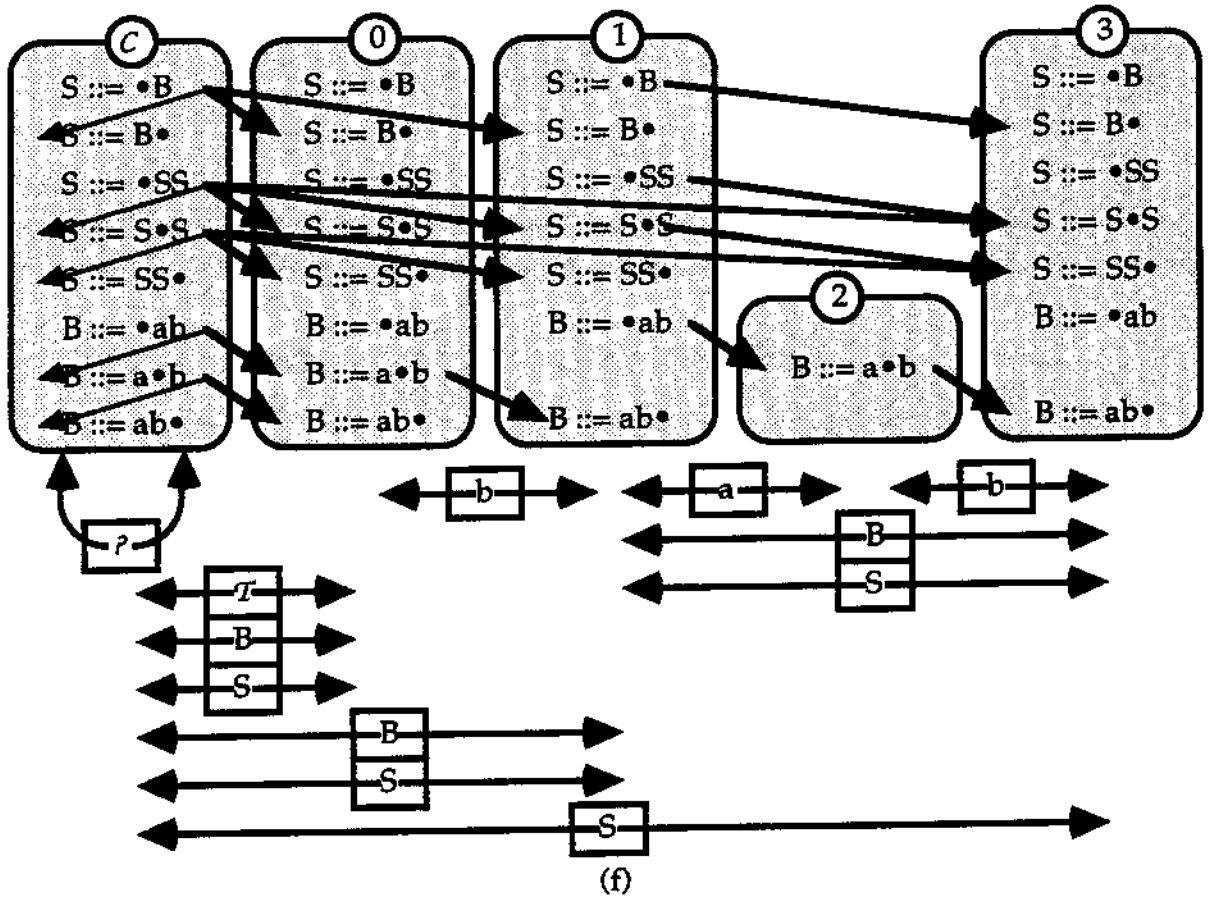
(d)


C
S ::= •B
B ::= B•
S ::= •SS
B ::= S•S
B ::= SS•
B ::= •ab
B ::= a•b
B ::= ab•
0
S ::= •B
S ::= B•
S ::= •SS
S ::= S•S
S ::= SS•
B ::= •ab
B ::= a•b
B ::= ab•
1
S ::= •B
S ::= B•
S ::= •SS
S ::= S•S
S ::= SS•
B ::= •ab
B ::= ab•
2
B ::= a•b
3
S ::= B•
B ::= ab•
b
a
b
?
T
B
S
B
S

(e)

Finally, we make a shift possibility for the last 'b' of the input string, between 2 and 3. The B::=a•b in 2 uses it, makes B::=ab• in 3, which is complete. This makes a shift possibility between 1 and 3. This is used by S::=•B in 1. This causes a shift possibility for S between 1 and 3 (e).

This S shift possibility is used by S::=•SS and S::=S•S, resulting in S::=S•S and S::=SS• in 3. The S::=SS• is compete, resulting in a shift possibility for S between *C* and 3. This is used by S::=•SS and S::=S•S, resulting in new links. At the end, the predictor adds S::=•SS, S::=•B and B::=•ab to 3. Then we are ready (f).



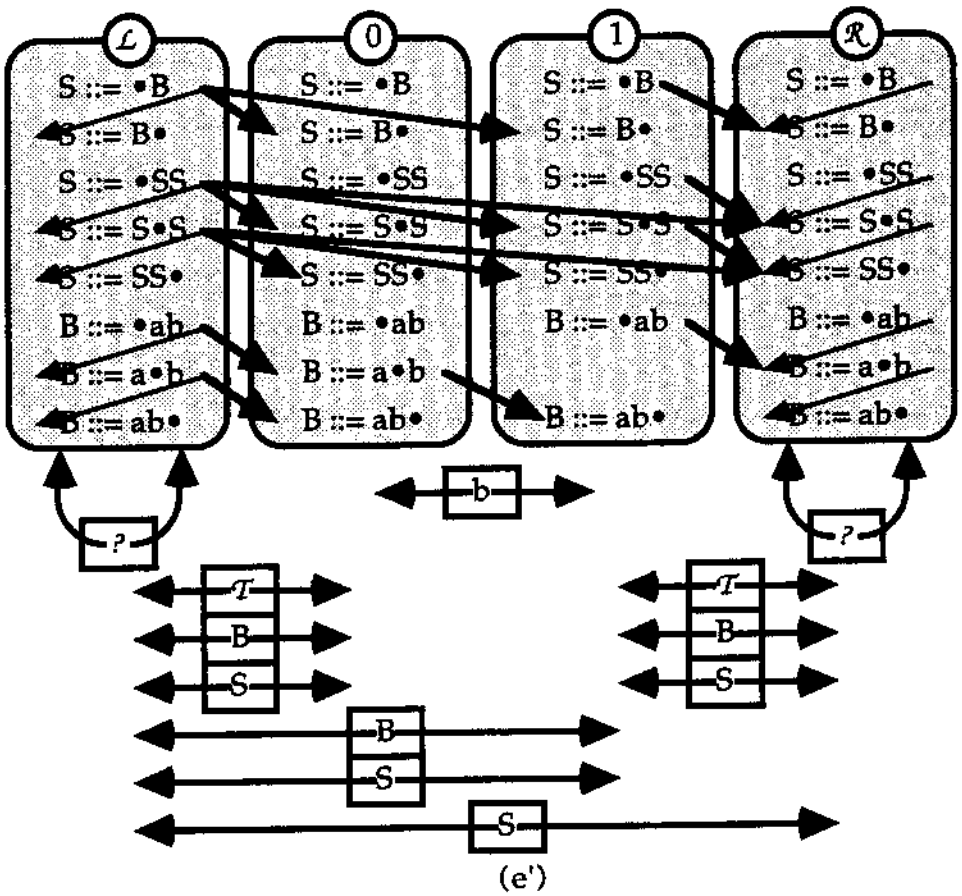
(f)

Switching the context to the other side

If we want to change the working direction, the context has to be moved to the other side. An easy way to do this is as follows. To distinguish between the two contexts, we call the left context $\mathcal{L}$ and the right context $\mathcal{R}$.

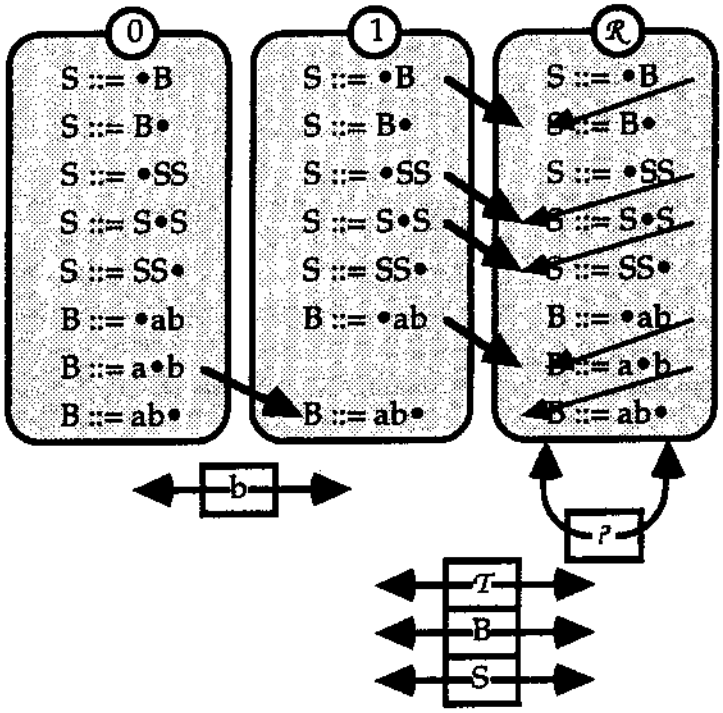
```
SwapContextToRight
      S := rightmost set
      L := left context set
      R := Make a new context set /* the new context set */
      put R at rightmost position
      Make a T shift possibility between S and R
      while an action is possible do action od
      remove(L)

remove (ItemSet)
      Remove all links to items in ItemSet
      Remove all shift possibilities between ItemSet and other sets
      Remove the items in Itemset
      Remove the emptied ItemSet
```

Example:
We start from situation (d) of the previous example. We want to add the missing 'a' at the left. Before this can be done, we need to move the context to the right. Therefore, we add a $\mathcal{T}$ shift possibility to a new context $\mathcal{R}$, and we do all actions (e').



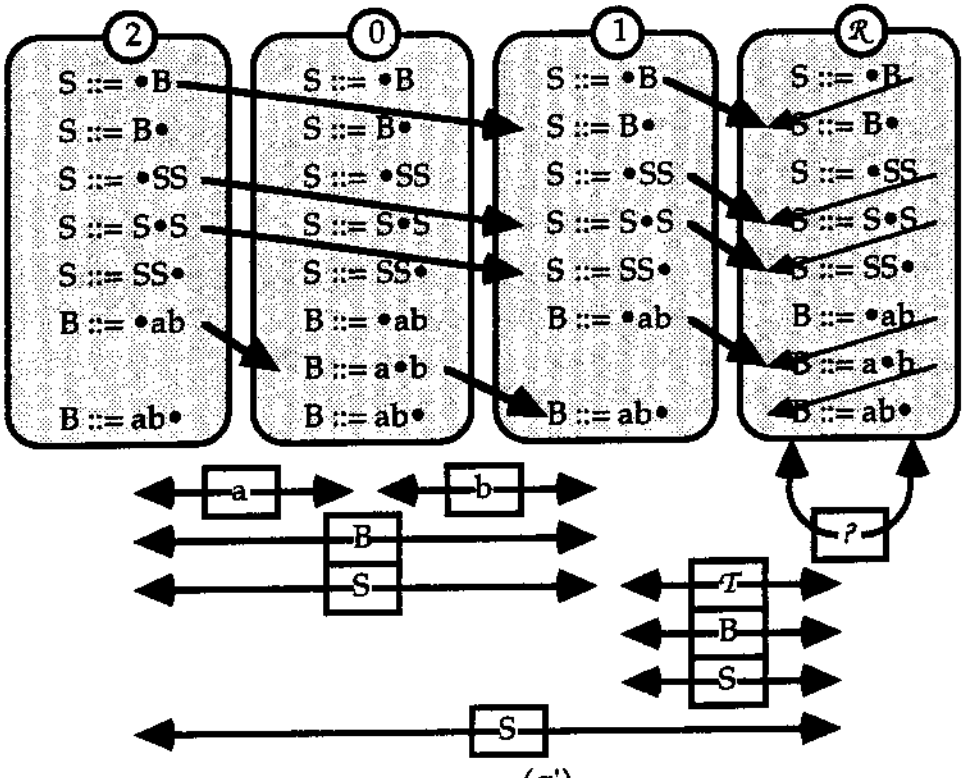
(e')

Next, we remove $\mathcal{L}$, resulting in (f').



(f')

We are ready to parse leftwards, so we add a shift possibility for 'a' between 0 and 2, with 2 at the left of 0, and we do the possible actions. The result is (g').



(g')

We found a successful parse for ab because of the shift possibility for S between 1 and 2, and we know that extending the context to the right may be successful because of the shift possibility between 2 and $\mathcal{R}$.

Deciding about the result

If we found a shift possibility between the left and the right normal set, we can accept the input. But if no such a shift possibility has been made, the next question is whether it is useful to try a larger context[1]. As we saw in several examples, we can decide for this by looking for shift possibilities using context. During parsing, we only have one context, say the left context. But it may be possible that the parsed input string can only be extended to the right. There can be no shift possibility representing this, as we assumed that there only was a left context. So to decide between failure and more context, we need both a left and a right context. We can make two contexts without problems, as we saw in the previous section. We only need to remove one of them when we want to continue parsing. The algorithm for deciding about the result is as follows:

```
decide_result (S)
      /* S is the needed topnode sort in the parse tree */
     U0 := leftmost normal set
     Un := rightmost normal set
     if there is a shift possibility for S between U0 and Un
     then return 'accept' fi

      /* no accept. Find a shift possibility using some context */
     if there is only one context then make other context fi
     L  := left context set
     R  := right context set
     if there is a shift possibility between L and (R or Un)
     or there is a shift possibility between U0 and R
     then return 'more-context'
     else return 'failure' fi
```

With the shift possibilities between left and right context as described here, it is possible to make a more sophisticated incremental parser than the one described in chapter 2. In the algorithm of chapter 2, we go to the parent when more context seems to be useful. The following options are not considered there:

- We can see what nonterminals will possibly result from more context by looking at the shift possibilities. For example if the parent is nonterminal Q, but we have no shift possibility for Q using context, we already know that that parse will not succeed (but both 'fail' and 'more-context' are still possible at node Q)
- If we have no shift possibilities using right context, but the node one higher has right context, we already know that we are in a 'failure' situation.

And there are other similar tests that can be done.

---

[1]The question whether we should return 'more-context' or 'failure', see chapter 2

An algorithm for island recognising

In this section, we will look at the methods that are needed for an island recogniser. 'new' makes a new recogniser, and 'extend' continues the recognising of some text in a given direction. It returns the result, either 'accept' (this is not a parser), 'more-context' or 'failure', conform to the ideas of chapter 2.

In the algorithms in chapter 4, there still is a left-to-right bias. This way, we prevented the addition of too much items. But now it is possible to turn the direction during recognising, returning the problem of addition of many items. For example, in example (g') two pages back, the shifter now can add B=a•b to set 1, because it is possible to shift the b using shift possibility $\mathcal{T}$ from $\mathcal{R}$. We did not do so, because this is not what we aimed for: we already added all the items that once might be important, before we continued with the next input symbol.
We solve the problem by only permitting addition of items to the last made itemset. To make this explicit, we use a global variable 'Outermost' indicating that item set.

Some definitions:

- We distinguish between 'normal' and 'context' itemsets. An itemset is 'context' if there is a $\mathcal{T}$ shift possibility between the set and itself.
- $\text{left}^{-1} = \text{right}$; $\text{right}^{-1} = \text{left}$
- S stands for a symbol, that is a (non)terminal. N stands for a nonterminal.
- In the actions, outermost is the rightmost set in left-to-right parsing. It is the only set that can be changed. Direction is the current working direction.
- Direction-most should be read as leftmost when Direction='left', and as 'rightmost' when Direction='right'. Direction is a global variable in this specification.

```
new (Grammar)
     start in an empty situation
     Direction := 'right'
     G := Grammar /* for later references to it */
     L := a new context itemset, at leftmost position
     Outermost := a new itemset with all dotted rules, at right of L
     make a T shift possibility between L and Outermost
     while an action is possible do action od

extend (X1..Xn,Direction,S)
      /* S is the needed sort in the parse tree */
     set_direction(Direction)  /* context at correct side */
     for 1≤k≤n with k counting in Direction do
          U := Direction-most itemset
          Outermost := a new Direction-most itemset without items
          make shift possibility for Xk between U and Outermost
          while an action is possible do action od
     od
     return decide_result(S)

set_direction (Direction)
     if not Direction-most itemset is a normal set then
```

```
        /* context at wrong side.. */
            if there is only one context then make other context fi
            remove(Direction-most itemset)
        fi
```

The possible actions, adapted to use Direction and Last:

```
scanner
        if Item in set A has dotted rule DR with an S at the
            Direction side of the •
        and there is a shift possibility for S between A and Outermost
        then
            Item' := add(DR with • moved 1 symbol to Direction)
            make a link between Item and Item', pointing to item
                with the • at right side of S
        fi

completer
        if Item with dotted rule N=•α in set A
        and Item' with dotted rule N=α• in set B
        and (A=Outermost or B=Outermost) and Item ↠* Item' then
            make new shift possibility for N between A and B
        fi

predictor
        if Item in Outermost has N at Direction side of the •
        and N::=γ is production of G then
             /* add item with this production and dot at start */
            DottedRule := N::=γ, with the • at Direction^-1
            add(DottedRule)
        fi

add (N=α•β)     /* returns item with this dotted rule in Outermost*/
        Item := find an item N::=α•β in Outermost
        if Item not found then
            add Item N::=α•β to Outermost
            if DottedRule is an empty production then
                make shift possibility for N
                between Outermost and Outermost
            fi
        fi
        return Item
```

We are getting close to the implementation, but before we give it, another problem has to be solved.

Building parse trees

As usual with parsing problems, we started building a parser, and ended up with a recogniser. In this section, we will turn the recogniser into a parser.

We have ended up with a situation containing a shift possibility from the leftmost normal to the rightmost normal set, producing the right nonterminal. The recogniser now simply returns 'accept', but the parser has to return a parse tree instead. We know two ways to derive parse trees when we have ended up with this situation:

1. Find out how the shift possibility was made. This can be done by searching a production rule for which there are adjacent shift possibilities, such that the left shift possibility starts in the leftmost normal set, and the right shift possibility ends in the rightmost normal set. This search seems to imply a lot of work. Even removing useless items (next section) seems of little use here.

2. When a shift possibility is made, remember how it was made. We can do so by remembering the links that were used, or better the shift possibilities that made these links possible. This way, the search of the solution 1 is avoided. Furthermore, the resulting data structure is very close to a parse tree.

We will use the second solution, because it makes deriving parse trees easy.
What happens with ambiguities? With the chosen solution, a shift possibility will be added twice, but with different used links. We can handle ambiguities in two ways:

1. Discard the second way to make this shift possibility. Although saving some storage, this does not seem to have any advantages.
2. Store the second way as alternative of the first way.

We will use the second way to handle ambiguities. The result is a way of storing parse trees similar to the structure described in [R92], Chapter 2. This way of storing parse trees may be expensive. For very ambiguous grammars, it will require exponential space to store the parse trees. In chapter 7, an idea to store them in $O(n^3)$ is described.

II: Removing useless items

Useless items are items that do not help in building a useful shift possibility. A shift possibility is useful if it helps us for deciding the result (so if it is a shift between the leftmost normal or context set and the rightmost normal or context set). A shift possibility is also useful if it helps creating a useful shift possibility, by making one of the links for it.

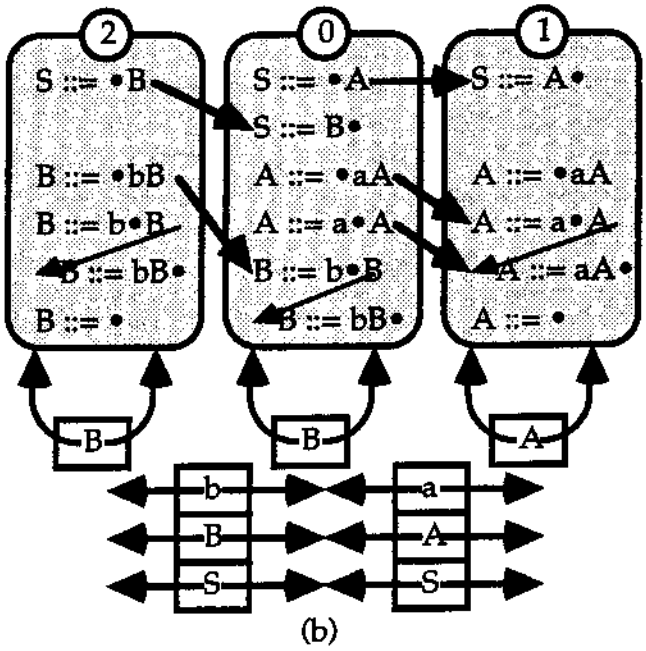
Example. Take the second grammar of this chapter,
Grammar:

S ::= A | B

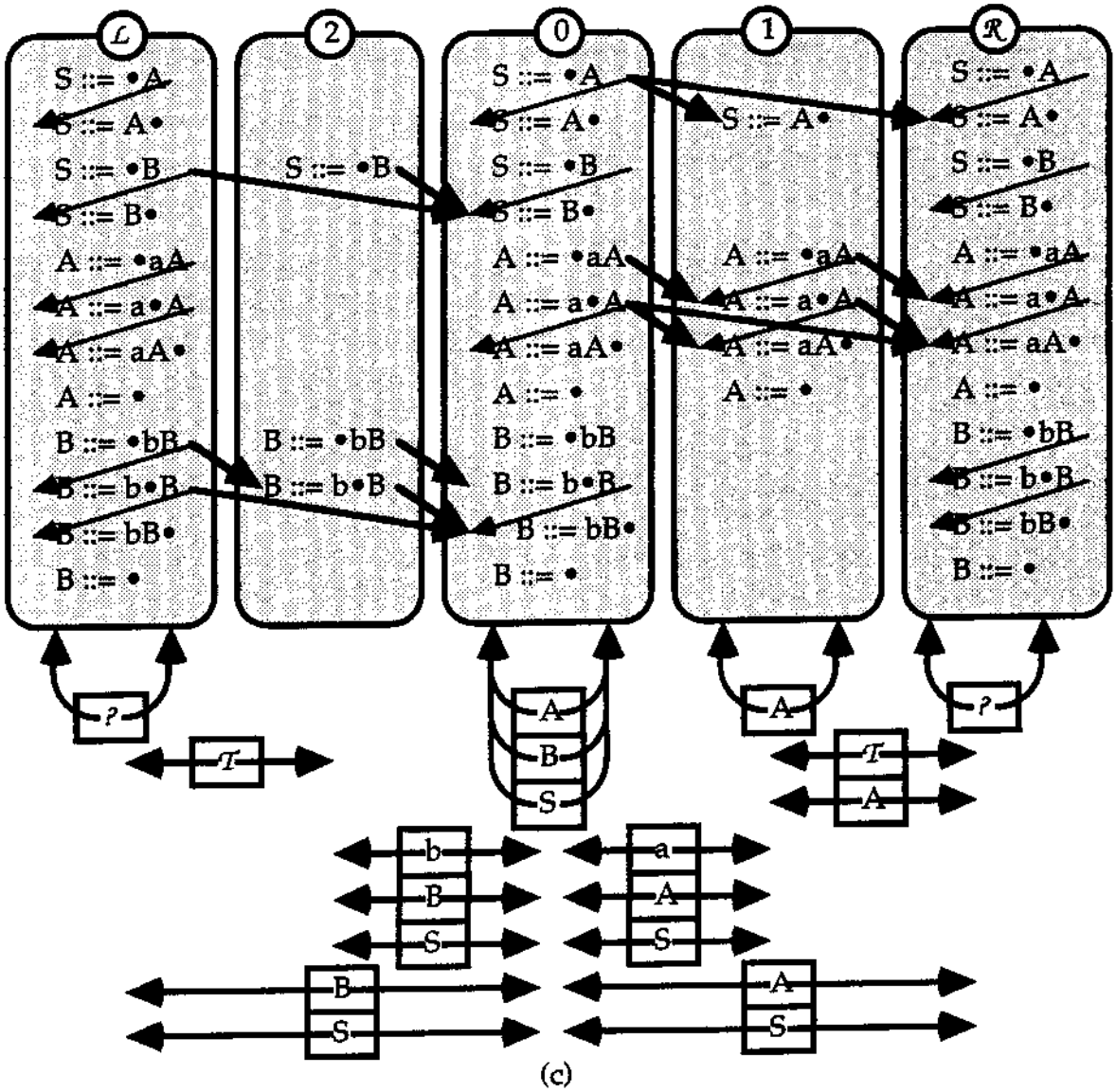
A ::= a A | ε

B ::= b B | ε

As shown there, we get situation (b) after giving a right context 'a', and a left context 'b':


2
S ::= •B
B ::= •bB
B ::= b•B
B ::= bB•
B ::= •
0
S ::= •A
S ::= B•
A ::= •aA
A ::= a•A
B ::= b•B
B ::= bB•
1
S ::= A•
A ::= •aA
A ::= a•A
A ::= aA•
A ::= •
B
B
A
b
B
S
a
A
S

(b)


ℒ
S ::= •A
S ::= A•
S ::= •B
S ::= B•
A ::= •aA
A ::= a•A
A ::= aA•
A ::= •
B ::= •bB
B ::= b•B
B ::= bB•
B ::= •
2
S ::= •B
B ::= •bB
B ::= b•B
0
S ::= •A
S ::= A•
S ::= •B
S ::= B•
A ::= •aA
A ::= a•A
A ::= aA•
A ::= •
B ::= •bB
B ::= b•B
B ::= bB•
B ::= •
1
S ::= A•
A ::= •aA
A ::= a•A
A ::= aA•
A ::= •
ℛ
S ::= •A
S ::= A•
S ::= •B
S ::= B•
A ::= •aA
A ::= a•A
A ::= aA•
A ::= •
B ::= •bB
B ::= b•B
B ::= bB•
B ::= •
?
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A
B
S
A
𝒯
A
?
b
B
S
a
A
S
B
S
A
S

(c)

We provided 'b a' to the parser, which is no string in L(G), and cannot be extended to be one either. We can see this by making two contexts. If we do so, the situation looks like (c). In this situation, we can see that more context does not help: there is no shift possibility between ($\mathcal{L}$ or 2) and (1 or $\mathcal{R}$). So there are no useful shift possibilities and no useful items. The aim of this section is to remove all useless items (this means, all the items in set 0,1 and 2 in case (c)!)
Another good example is picture (g'), on page 41. In set 0 for example, only B::=a•b is useful, because it is the only item that helps constructing a useful shift possibility between 2 and 1.

An invariant for the items

In fact, we want the items to fulfil the following invariant:

If we have processed input $X_1 .. X_n$, and we have itemsets $U_0 .. U_n$, then:

$$\text{Item with dotted rule } N=\alpha\bullet\beta \in U_k$$
$$\Leftrightarrow$$
$$\exists N': N' \Rightarrow^* \gamma N\delta \Rightarrow \gamma\alpha\beta\delta \wedge \gamma\alpha \Rightarrow^* \omega X_1..X_k \wedge \beta\delta \Rightarrow^* X_{k+1}..X_n\omega' \text{ for some } \omega,\omega'$$

That is, we want each item to have possibilities to be fit into a derivation that has $X_1..X_n$ as (sub)string of L(G) ([RK90]). We say that an item is **useful** if it fulfils this invariant. An item is **useless** if it does not.

Note that the context sets do not fit into this invariant notation because they are not an U_k in our notation. Furthermore, an item in L can contain items that produce many context before actually producing $X_1..X_n$. So if we want an invariant for the context, it is like

$$\text{Item with dotted rule } N=\alpha\bullet\beta \in \mathcal{L} \Leftrightarrow \exists N': N' \Rightarrow^* \gamma N\delta \Rightarrow \gamma\alpha\beta\delta \wedge \beta\delta \Rightarrow^* \rho X_1..X_n\sigma$$

$$\text{Item with dotted rule } N=\alpha\bullet\beta \in \mathcal{R} \Leftrightarrow \exists N': N' \Rightarrow^* \gamma N\delta \Rightarrow \gamma\alpha\beta\delta \wedge \gamma\alpha \Rightarrow^* \rho X_1..X_n\sigma$$

We will only remove useless items from the normal item sets, and not look at the context sets. It is not very hard to do so, but we introduced a context set as a set with all dotted rules, which conflicts with the idea of removing items from it. Furthermore, we do not see any advantages in doing so.

A solution for removing useless items

A solution to find useful items is to mark the useful shift possibilities, like we noted in the examples. If a shift possibility is marked as useful, we can conclude that the items that were needed for that shift possibility are also useful. For example, if a shift possibility for S between A and B is known to be useful, and we know that that shift possibility was made by using the production S::=aSb, the items S::=•aSb in set A and S::=aSb• in set B are useful. Note that we can easy decide the rule and and shift

possibilities that were used for making a shift possibility by remembering the cause of a shift possibility when we make it, and do not discard ambiguities, like described in the section 'Building parse trees'.
But what to do with the other items? In our example, the items between S::=•aSb and S::=aSb• (some items with dotted rule S::=a•Sb and S::=aS•b) are also useful. In our solution, we do not recognise them as useful, but they will be save as long as they are 'hanging' with their links between two useful ends.

This approach gives the following algorithm:

```
remove_useless
     mark all items and shiftpossibilities as useless
     for  each ShiftPoss between (leftmost normal or context set)
          and (rightmost normal or context set)
     do useful(ShiftPoss) od
     for each ShiftPoss marked with useless do remove ShiftPoss od
     for each unmarked left- or right-complete Item
     do remove(Item) od

useful (ShiftPoss)
     if ShiftPoss already marked as useful then return fi
     mark ShiftPoss as useful
     for each way to make ShiftPoss do
          'N::=α' := rule that was used
          mark item in left set that ShiftPoss points to
               that has dotted rule N::=•α
          mark item in right set that ShiftPoss points to
               that has dotted rule N::=α•
          for  each ShiftPoss' used for one of the links
               between these two items
          do useful(ShiftPoss') od
     od

remove (Item)
     for each Link between Item and Item' do
          remove Link
          if   Item' now has no more links at the side
               where we removed the link
          then remove(Item') fi
     od
     remove Item
```

Incremental removal of useless items

In this section, we will try to make the removal of useless items incremental. At first glance, one thinks that there must be an easy way to remove them, directly after the parser is extended with one terminal. It seems easy to see which items can not do their shift, remove them and check whether this influences other items. Once an attempt is done to make an algorithm for it, this approach turns out to give troubles. We will try to show the problem with an *incorrect* algorithm.

Consider the following incremental 'solution'.

Assume that there is a left context, and we are parsing to the right. The general idea is to mark the items that can 'reach the right side'. Since any item reaches the left side because of the way we add items, we expect that the marked items are useful. After the marking process, we remove all unmarked items. We have 2 possible marks: needed (N) and reaches right side (R). An item is marked N if another item uses the shift it produces. An item is marked R if it is uplinked to an item in the rightmost set, or wants to shift a nonterminal and there is a rule producing that nonterminal in the same set, marked with R. Furthermore, we have an ordering on this marks: R>N>no mark. Each item prefers the highest possible mark. If this approach would work, we could try to update the marks in an incremental way.

```
remove_uncompletables(ItemSets)
      for each Item do Item.mark := no mark od
      for each Item in rightmost itemset do Item.mark := R od
      while an action is possible do action od
      for each Item with Item.mark = no mark
      do remove item and links od
       /* note that we do (can) not remove shift possibilities. */
```

We have the following actions to give Item higher mark. An action is only done if it gives a higher mark to Item.

```
use_mark_of_neighbour
      if ∃Item ↠ Item'
      then Item.mark := Item'.mark fi

someone_needs_us
      if ∃Item' with dotted_rule M ::= βN•γ in Uk
      and Item'.mark = N or R  /* item is useful */
      and ∃Item with dotted_rule N ::= α• in Uk
       /* then mark all rules that produce needed nonterminal */
      then Item.mark := N fi

some_item_is_working_for_us
      if ∃Item with dotted_rule M::= α•Nβ in Uk
      and ∃Item' with dotted_rule N ::= •γ in Uk
      and Item'.mark = R
      then mark item with R fi
```

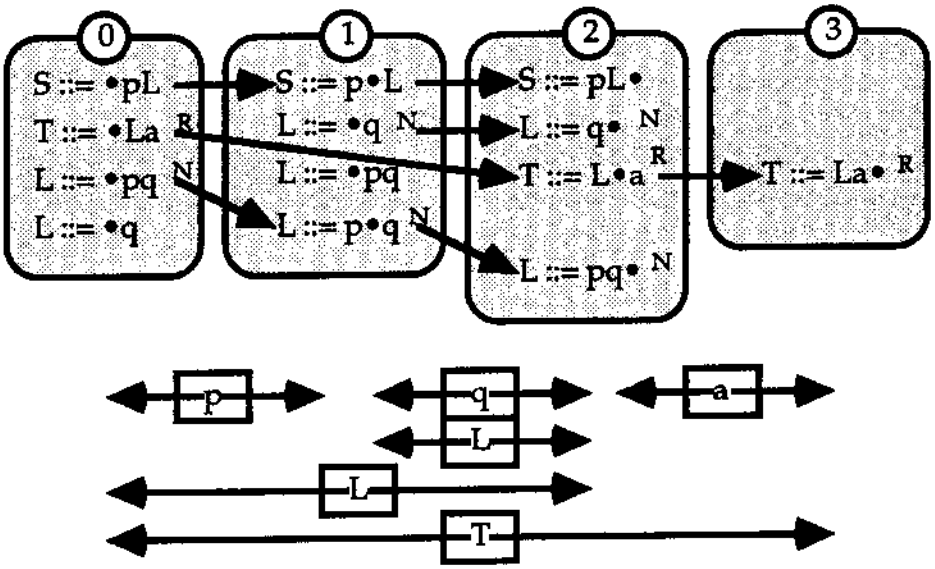
The following example shows where this algorithm fails in removing some items. The algorithm works incorrect in the someone_needs_us action, where all the dotted rules are marked that produce a nonterminal that is shifted by a useful item, which is an overkill.

Counter example:
Grammar:

S ::= p L
T ::= L a
L ::= q | p q

Input sentence: p q a

The resulting situation after processing input (for ease, we do a normal parse, starting only with productions with the • on the left) and marking all items is (a):



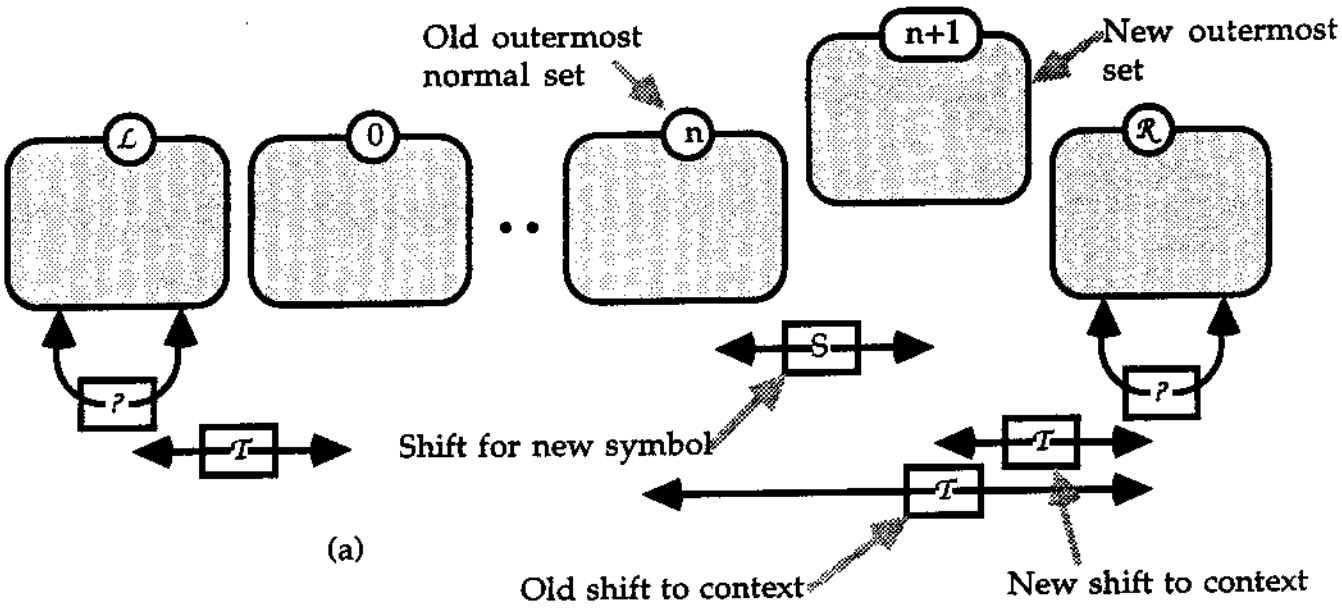
(b)

The L::=q• item in 2 is useless because it builds no subtree for the T::=L a production. So it should not be marked. The problem is that the L::=q• is marked because T::=L•a can reach set 3. But actually, not the L::=q but the L::=p q production caused the T::=L•a to appear.

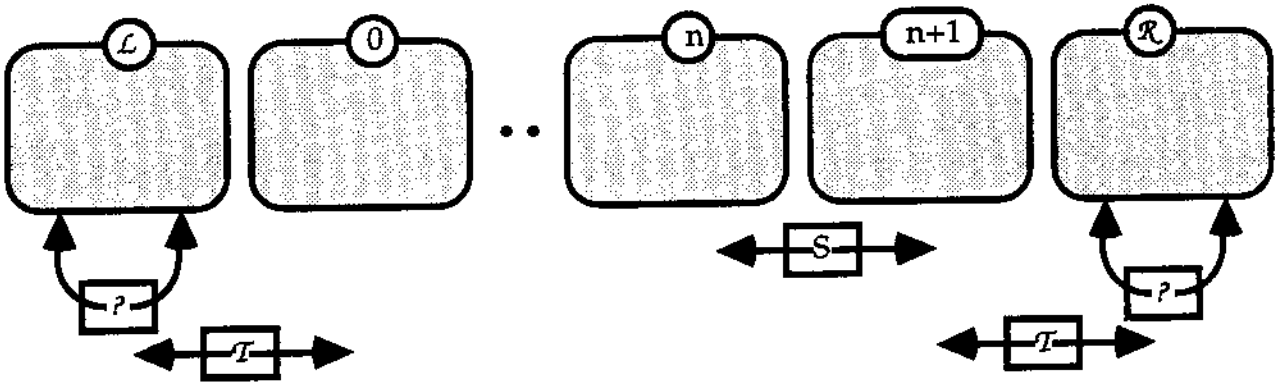
This problem can be solved by making a link from the T::=L•a item to the L::=pq• item, indicating that this item caused the T::=L•a to be added. The problem with this approach is that it is not symmetric. The problem can also be solved by making a link from the L::=pq• item to the L shift possibility from 0 to 2, the shift possibility it caused to be added. This looks more symmetrical, since both L::=•pq and L::=pq• can get such a link. But in fact, this looks like another way to get the first solution we gave.

A better way to make removing of useless items incremental is to make the first solution incremental. Therefore, it seems necessary for all shift possibilities and items to remember why they are useful. For the shift possibilities, this implies that they have to remember all shift possibilities that made them useful. For left- and right-complete items, this implies that they have to remember the shift possibilities that used them for constructing their shift.

The algorithm we think of maintains both a left and a right context *during parsing*. More context symbols are inserted by making a shift possibility for that symbol between the outmost normal set and a new set, and a τ shift possibility from that new set to the old context (a).



Next, the old $\mathcal{T}$ shift possibility from the old outermost normal set to the old context is 'retracted' in an incremental way, with remove_shift (b).




```
remove_shift (ShiftPoss)
     remove the ShiftPoss
     for each left- and right-complete Item that ShiftPoss
          could use for its shift do
          forget that Item was useful because of ShiftPoss
          if Item knows no more useful shift possibilities
          then remove(Item) fi
     od
     for each ShiftPoss' that was useful because of ShiftPoss do
          forget that ShiftPoss' was useful because of ShiftPoss
          if ShiftPoss' has no other reasons to be useful
          then remove_shift(ShiftPoss') fi
     od
     for each link that uses ShiftPoss do remove link od
```

We will not work out this algorithm in more detail. The reason is that (at least?) two things are remembered in duplicate:

1. Shift possibilities remember their children, and their children remember the shift possibility that made them possible.
2. Links remember the shift possibility that makes them possible, and shift possibilities what links they made.

This duplication seems waste of space and computation time. But it is not clear how this can be done better. This duplication of data seems closely related to the aim of incrementality.

6 An implementation of an Island Parser

Implementation in pseudo-Pascal

In this chapter, we gather all the results of chapter 4 and 5 to make an island parser. The methods we provide are **new** and **extend**. With this, we can make an incremental parser in the same way as the DecideResult' test of chapter 3, with the difference that the island parser only needs the new symbols and not the old as well. In Chapter 9, a Lisp implementation is given. The objects we use look as follows:

```
object 'ParserObject':          /* A parse situation consists of */
        itemsets                /* a list of our itemsets. Ordering is important */
        outermost               /* the direction-most itemset=the only changing set*/
        shift_possibilities     /* a set of shift possibilities */
        G                       /* the grammar */
        direction               /* the direction we're working in */

object 'itemset':
        items                   /* a set of items */
        type                    /* is it a 'normal' or a 'context' set? */

object 'ends':                  /* many things consist of two sides.. */
        left                    /* a left */
        right                   /* and a right side */

object 'item':
        dotted_rule
        links                   /* an ends-object: */
                                /*  in 'left' the links to us, in 'right' links from us */
        itemset                 /* the itemset where this item is in */

object 'link':
        arrow                   /* an ends-object: link from left to right */
        shift_possibility       /* who made this link possible */

object 'shift_possibility':
        symbol                  /* the recognised symbol */
        sets                    /* an ends-object containing the sets between which
                                /* this shift_possibility is */
        alternatives            /* different ways to make this shift possibility */

object 'alternative':           /* an alternative to make a shift possibility */
        production              /* the production that was used */
        shifts                  /* the shift possibilities that were needed to complete
                                /* that production */
```

'no_alternative' represents an object without production and shifts. It is used for the leaves, which are not produced. Self indicates the ParserObject we are talking about. Field names of the ParserObject refer to the 'Self' object that is passed in all functions. For example, 'itemsets' is short for Self.itemsets; 'direction' is short for Self.direction etcetera. Variables (excepted some index variables) and parameters start with an upper case character. We use ≈ to indicate matching symbols. e.g. 'a'≈'a'≈$\mathcal{T}$≈? and 'S'≈?.
The methods now look as follows:

```
new (Grammar)   /* returns a new, empty ParserObject */
     L := make a context set
     U0 := make a normal set
     Self := make an empty ParserObject, with
          G=Grammar, direction='right', itemsets=list of L and U0,
          outermost=U0
     for each possible DottedRule of G
     do add(Self,DottedRule) od
     add_shift_possibility(Self,𝒯,L,'no_alternative')
     return Self

extend (Self,X1..Xn,Direction,Symbol)
     /* Symbol is the topnonterminal we want in parse tree*/
     /* ? if any top symbol is OK */
     set_direction(Self,Direction) /* context at correct side */
     for 1≤k≤n with k counting in Direction do
          U := outermost
          outermost := a new Direction-most 'normal' itemset
                without items
          add_shift_possibility(Self,Xk,U,'no_alternative')
     od
     return decide_result(Self,Symbol)
```

We used the following help functions. The actions are implemented as follows: each action tests whether its action triggers other actions. If this is the case, these actions are called.

```
set_direction (Self,Direction)
      /* first check if we are in the right situation */
     if Direction-most itemset is a normal set then return fi
      /* no. Make 2 contexts and remove the old one */
     make_context(Self) /* if it already is there nothing happens */
     remove the Direction-most context set
     direction := Direction
     outermost := Direction-most itemset

predictor (Self,N)   /* Add N-producing rules to outermost */
     for each Rule in G do
          DottedRule := Rule with the • at direction-1
          add(Self,DottedRule)
     fi
```

```
add (Self,N::=α•β)   /* add item to outermost */
     Item := find an item with dotted rule N::=α•β in outermost
     if Item not found then
          Item := an item-object with dotted_rule=N::=α•β,
               links=an new empty ends-object, itemset=outermost
          add Item to outermost
          if α=β=ε then
               Alt := an alternative-object with
                    production='N=ε', shifts=empty list
               add_shift_possibility(Self,N,outermost,Alt)
          else
               S := symbol directly at direction side of • in N=α•β
               if S exists then
                    /* Check for predictor and scanner actions */
                    UsableShifts := set of all shift possibilities
                         in shift_possibilities with
                         sets.direction^-1=outermost and symbol≈S
                    for each ShiftPoss in UsableShifts
                    do shift(Self,Item,ShiftPoss) od
                    if S is nonterminal then predictor(Self,S) fi
               fi
          fi
     fi
     return Item

add_shift_possibility (Self,S,FromSet,Alternative)
     /* make a shift poss. for S between FromSet and outermost */
     Ends := a new ends-object
     Ends.direction^-1 := FromSet
     Ends.direction := outermost
     find in shift_possibilities a ShiftPoss with
          sets=Ends and symbol≈S
     if ShiftPoss is found then
          add Alternative to ShiftPoss.alternatives
          /* it existed already so no check for items using it */
     else
          /* create new shift poss and check who uses it */
          ShiftPoss := a new shift_possibility object with symbol=S,
               sets=Ends, alternatives={ Alternative }
          add ShiftPoss to shift_possibilities
          /* and check whether this causes new links */
          Items := all items in FromSet having a dotted rule
               with a symbol≈S at direction of •
          for each Item in Items do shift(Self,Item,ShiftPoss) od
     fi
```

shift is the most difficult function in our situation. It makes a new link to an item. The item can already exist, but the link can not, since shift can be called in two ways:

1. From add_shift_possibility, which only calls shift when the shift possibility for the link did not exist, so the link can not exist.
2. From add, which only calls shift when the item did not exist, so a link between that item and other items can not exist.

```
shift (Self,Item,ShiftPoss)     /* Item can use ShiftPoss */
      /* ShiftPoss.direction should be outermost !! */
      /* shift makes a new link to an item. */
     ShiftedRule := Item.dotted_rule,
          with • moved one symbol to the direction
     NewItem := add(Self,ShiftedRule)
     Arrow := a new ends-object
     Arrow.direction := NewItem
     Arrow.direction^-1 := Item
      /* Now create the link */
     L := a new link-object, with arrow=Arrow,
          shift_possibility=ShiftPoss
      /* link to right for left item, and to left for right item */
     add L to Arrow.left.links.right
     add L to Arrow.right.links.left
     ToComplete := a new ends-object
     ToComplete.direction :=
          shifts_to_complete(Arrow.direction,direction)
      /* Check if item completed in the working direction */
     if ToComplete.direction=nil then return fi
      /* complete! now check for the other direction */
     ToComplete.direction^-1 :=
          shifts_to_complete(Arrow.direction^-1,direction^-1)

     Production := remove the dot from Item.dotted_rule
     Symbol := nonterminal that is produced by Production
     for each combination of a LeftToComplete in ToComplete.left
          and a RightToComplete in ToComplete.right
      /* For each such combination, a shift poss can be made! */
     do
          if direction='right'
          then From := LeftToComplete.endset
          else From := RightToComplete.endset fi
          Alternative := a new alternative-object, with
               production=Production,
               shifts=append LeftToComplete.shiftlist,
                    ShiftPoss and RightToComplete.shiftlist
          add_shift_possibility(Self,Symbol,From,Alternative)
     od
```

When a new link is made, we need to check if it makes items complete. Therefore, we need to follow all the arrows in two Directions and give all the ways to reach a complete item. This function looks in the given way, starting at a given item. It returns a set containing all possible shift-to-complete objects:

```
object 'shift-to-complete':     /* one way to reach a dir-complete item */
     shiftlist                  /* shifts to be done up to a complete item */
     endset                     /* in which set was the complete item */
```

```
shifts_to_complete (Item,Direction)
     if Item.dotted_rule has the • at Direction
     then
          ShiftToComplete := a shift-to-complete-object, with
               shiftlist=empty list, endset=Item.itemset
          return { ShiftToComplete }
     else /* Item is not complete, look back */
```

```
            ShiftsToComplete := ∅
            for each Link in Item.links.Direction do
                 ShiftsToComplete' :=
                      shifts_to_complete(Link.arrow.Direction
                           ,Direction)
                 LinkShift := Link.shift_possibility
                 for each ToComplete' in ShiftsToComplete' do
                      append LinkShift at Direction^-1-side of
                           ToComplete'.shiftlist
                 od
                 add ShiftsToComplete' to ShiftsToComplete
            od
            return ShiftsToComplete
       fi

decide_result (Self,Symbol)
       U0 := leftmost normal set
       Un := rightmost normal set
       if there is a ShiftPoss in shift_possibilities
            for a symbol≈Symbol between U0 and Un
       then return select_a_tree(ShiftPoss) fi
        /* no tree. Find a shift possibility using some context */
       make_context(Self)
       L  := left context set
       R  := right context set
       if there is a shift possibility between L and (R or Un)
       or there is a shift possibility between U0 and R
       then return 'more-context'
       else return 'failure' fi
```

Since we need two contexts for the remove_useless algorithm, and because there are two contexts when make_context is called, it is attractive to have make_context to remove useless items directly. Without it, the algorithm also works correct.

```
make_context (Self) /* add a context at end of working dir */
       Un := outermost
       if Un.type='context' then return fi
       outermost := a new direction-most context set
       add_shift_possibility(Self,T,Un,'no_alternative')
        /* The following call is optional */
       remove_useless(Self)

select_a_tree (ShiftPoss)
        /* returns one tree derived from the cyclic parse forest
        /* that we created. This job is not trivial but outside the
        /* scope of this algorithm */
```

If remove_useless is used, the objects 'item' and 'shift_possibility' need an additional 'mark' field.

```
remove_useless(Self) /* both contexts required */
       make_context(Self)
       for each normal ItemSet do
            for each Item in ItemSet do Item.mark:=false od
       od
```

```
      for each ShiftPoss in shift_possibilities
      do ShiftPoss.mark:=false od
      L := leftmost context set
      U0 := leftmost normal set
      Un := rightmost normal set
      R := rightmost context set
      for each ShiftPoss in shift_possibilities
           with ShiftPoss.sets.left=L or U0
           and ShiftPoss.sets.right=R or Un
      do   useful(ShiftPoss) od
      shift_possibilities := {SP∈shift_possibilities | SP.mark=true}
      for each normal itemset Uk do
           for each Item in Uk with Item.mark=false
                and (Item.links.left=∅ or Item.links.right=∅)
           do remove(Item) od
      od

useful(ShiftPoss)
      if ShiftPoss.mark=true then return fi /* already done */
      ShiftPoss.mark := true
       /* now mark the other shift possibilities that this ShiftPoss
       /* needs to be created (all alternatives) and
       /* the items that were used */
      for each Alternative≠'no_alternative' in ShiftPoss.alternatives
      do
           'N::=α' := Alternative.production
           for each ShiftPoss in Alternative.shifts
           do useful(ShiftPoss) od
           mark item with dottedrule N::=•α in ShiftPoss.sets.left
           mark item with dottedrule N::=α• in ShiftPoss.sets.right
      od

remove(Item)
      for Side in {'left','right'} do
           for each Link in Item.links.Side do
                LinkedItem := Link.arrow.Side
                remove Link from LinkedItem.links.Side-1
                if LinkedItem.links.Side-1=∅
                then remove(LinkedItem) fi
           od
      od
      remove Item from Item.itemset
```

A notion of correctness

We have no proof of correctness for our algorithms. To give an idea of correctness, we can show two things:

1. If the input string is in L(G), a shift possibility representing this can be made by means of (some of) the actions.
2. This implementation does all possible actions.

Point 2 seems easy to proof: each action checks for the need to trigger other actions due to his own action. Proving point 1 seems more complicated.

7 Optimizations

Goal of this chapter

In this chapter, we have a brief look at alternative solutions for several problems, and look whether these ideas can improve our algorithms. This chapter considers the following points:

- alternative ways to make an island parser
- relations with Tomita's parser
- optimizations for our island parser

Alternative ways to make island parsers

The first idea is to adapt the substring parser ([RK90]) for island parsing. This is an adapted Tomita parser, that invents symbols when a reduce beyond the stack boundaries is attempted. The substring parser can parse only from left to right. If we want to extend a parse to the right, we can simply go on parsing from the situation just before the end-of-input symbol was scanned. If we want to extend a parse to the left, we start a new substring parser at the left of the new context, and parse until we reach the part that we already parsed. Then, we need to attach the parse stacks to each other.
The substring parser invents the missing symbols. But in our case, we may not invent symbols, since the actual context may be given in a next call to extend. Instead, we block the parsers that try to reduce beyond their stack boundary, until their stack is large enough to do a complete reduction. This blocking causes troubles because the blocked parsers cannot go on scanning the input. So when they get unblocked their scanning position is wrong. Furthermore, we need to keep *any* peace of produced stack in stead of only the stacks under the running parsers, to prevent double work. This may cause high overhead.
If we unblock a parser, and after a few actions we can attach its stack to an existing part, we need to replay all reduce actions ever done over that stack, now using the new stack part we just connected.
A specification for this idea is not very difficult, but an efficient implementation for it seems hard. Furthermore, this approach lacks the symmetry that we think to be essential to the problem.

A second idea seems more practical: just start a left-to-right parser and use it when more right context is provided, and start a right-to-left parser using the reversed grammar when left context is provided. This approach has been used in [S90], but an algorithm is not worked out there. With this idea, we still have to keep track of the reductions that are done over the boundary between these two parsers.
Although not clear from [S90], the parsers need to know at what position in the input they started parsing after the last communication. This is because a communication between two parsers is only allowed if the trees they already built cover the same part of the input symbols.

With this, we get the following data structure for a parser:

```
object 'Parser':
      direction        /* working direction, left or right */
      startpos         /* Start position after last communication */
      otherstartpos    /* Start position of other parser after last communication */
      scanningpos      /* our current scanning position */
      stack            /* our stack */
      situation        /* the things we're doing. usually 'parsing' */
```

We will not describe a complete algorithm, but only sketch some actions to give an idea of what has to be done. We only describe the allowed actions, not the parsing itself, as this is done in the same way as Tomita's parsing algorithm. stack is short for Parser.stack. Initially, in each possible state S of the L→R table a left-to-right parser with S on the stack is started, and similar for the R→L table, like in the substring parser ([RK90]).

```
shift (Parser,state')
     push state' on stack

error (Parser)
     remove Parser from set of active parsers

reduce (Parser,A ::= αβ)  /* α,β may be ε. */
     if there are at least |αβ|+1 entries on stack
     then
          pop |αβ| entries from stack
          push GOTO(top of stack,A) on stack
     else
          there are only |β| entries on the stack
          block(Parser,"A ::= α•β")
           /* The block function handles unblocks */
     fi

block (Parser,A ::= α•Sβ) /* One state is always on the stack */
      /* A::=α•Sβ means that only |β|+1 entries are on the stack */
      /* and the parser tried to reduce according to A::=αSβ */
     Parser.situation := Situation
     for each blocked Parser'
     with Parser'.direction=(Parser.direction)^-1
     and Parser'.situation="A::=β^-1•Sα^-1"
     and Parser'.startpos = Parser.otherstartpos
     do   complete reduction of Parser and Parser', by using the
               α of Parser', S and the β of Parser
          if both parsers have no remaining context
          and A=Start nonterminal of used grammar
          then we found a successful parse fi
          restart(Parser,A,Parser'.scanningpos)
          restart(Parser',A,Parser.scanningpos)
     od
```

```
restart (Parser,Symbol,OtherParserStartPos)
     if never restarted a parser after recognising Symbol
     with the same scanningpos then
          for each State that can be reached directly by a Symbol
               transition
          do   make a new Parser'
               with direction=Parser.direction,
               startpos=scanningpos=Parser.scanningpos,
               otherstartpos=OtherParserStartPos,
               stack contains only State,
               situation='parsing'
          od
     fi
```

Some problems with this algorithm are:

- It is difficult to see that it is correct.
- The synchronization is lost, because some parsers can be delayed while waiting for the other side to give some missing parts. Because of this we need to keep parts of the stack that could be removed in normal Tomita parsing, to prevent duplication of work. This makes the algorithm waste some storage space.

Relation between Tomita's and our parser

Tomita made a parser that uses parse tables in stead of bare grammar ([T85]). It may be attractive to use parse tables, since it is a way to do some preprocessing over the grammar. What exactly is preprocessed by building a parse table? It mainly combines uncertainties related with future input symbols. Say, we want to recognise an S, but both S=•ab and S=•ac can be used when we see the first a. In our case, we shift both items. Tomita's table catches this case in one, because there is a state in his table representing that both S=a•b and S=a•c are applicable.

Can we adapt this idea for our own parser? It seems hard to do so. The problems we encountered are caused by the need to parse in two directions, while Tomita's idea basically works with extension to one side. We have no good ideas to solve this problem.

Optimization ideas for our island parser

There are a number of possible optimizations and attempts for optimization for our parser. We will give a short overview, and then work out the last two in more detail.

1. Because a link is a reflection of a shift possibility, the link can reuse the sets object of the shift possibility.

2. We expect that many optimizations as described in [GHR80] can be applied to our algorithm.

3. In the algorithm for removing useless items, it is possible to use a new mark in stead of deleting all old marks.

4. In our shift algorithm, a check is done whether the item is complete, by first looking in the working direction. It is inefficient to use the all-paths scanning function 'shifts_to_complete' in this case, since there will be at most one link from an item in the outermost set in the working direction. Furthermore, if something is returned, the 'endset' of the returned shift-to-complete object is not interesting, since it always will be outermost. An algorithm that returns 'direction-complete' or 'not direction-complete' would be sufficient.

5. A context is basically the same in all cases. Making the context implicit might improve the performance.

6. Because of the way we store parse trees by storing alternatives in the shift possibilities, the space complexity may be exponential in the number of input symbols. This is the case with very ambiguous grammars. We have an idea to solve this problem, by improving the data structure for storing parse trees. We expect that this will also improve the performance of the parser in general, since we do not need to build the alternative-objects.

An implicit context

The idea is implemented by making a special link indicating that a link to a context is ment. This way, we do not need to make the context itself. If we use such an implicit context, we still need to do the same actions as in the case that a context was present. Therefore, we keep the idea that there are $\mathcal{L}$ and $\mathcal{R}$ contexts, but these are not represented by itemsets. Shift possibilities to a context get a special pointer at the side where they need to point to a context. It is easy to correct the specification, by doing as if the link exists if there is a shift possibility to the context by extending the definition for $\twoheadrightarrow$:

Item with dotted rule $N::=\alpha S \bullet \beta$ in U_k and $\exists$shift possibility for S between $\mathcal{L}$ and U_k

$$\Rightarrow$$

GhostItem with dotted rule $N::=\bullet \alpha S \beta \twoheadrightarrow$ Item

and

Item with dotted rule $N::=\alpha \bullet S \beta$ in U_k and $\exists$shift possibility for S between U_k and $\mathcal{R}$

$$\Rightarrow$$

Item $\twoheadrightarrow$ GhostItem with dotted rule $N::=\alpha S \beta \bullet$

So we do as if there is a link when there is a corresponding a shift possibility. In the usual case, this is not correct. But in the case that one side is a context set, it is correct. This is so because in the island parser, a link to a context exists if and only if there is a corresponding shift possibility. This can be seen in the following way: if, in the island parser, a new shift possibility is made *to* a context (in this case, we are at work in the context), all items that can make a link will do so. The other way round, if a shift possibility is made *from* a context, any item that can shift to the context will be uplinked, because the context contains all possible items.

It is less easy to implement this idea. The only working solution we know is to 'reconstruct' (in an implicit way) the context that is missing, and do the actions as if it were there. We will describe what has to be changed in our parser to use implicit contexts.

new: no context has to be made. The $\mathcal{T}$ shift possibility between $\mathcal{L}$ and U_0 now does not result in a link to a context.
extend: stays the same.
set_direction: in stead of testing for Direction-most set to be a normal set, we need to check for the existence shift possibilities to $\mathcal{L}$ or $\mathcal{R}$.
predictor: stays the same.
add: stays the same.
add_shift_possibility: if FromSet is a context set and the ShiftPoss did not yet exist, we only need to shift all items from the context to the outermost set. No link has to be made, since the shift possibility represents the links. The algorithm now becomes:

```
add_shift_possibility (Self,S,FromSet,Alternative)
      /* Make shift poss. for S between FromSet and outermost */
     Ends := a new ends-object
     Ends.direction^-1 := FromSet
     Ends.direction := outermost
     find in shift_possibilities a ShiftPoss with
          sets=Ends and symbol=S
     if ShiftPoss is found then
          add Alternative to ShiftPoss.alternatives
           /* it existed already so no check for items using it */
     else
           /* create new shift poss and check who uses it */
          ShiftPoss := a new shift_possibility object with symbol=S,
               sets=Ends, alternatives={ Alternative }
          add ShiftPoss to shift_possibilities
          if outermost = a context then
                /* we made an implicit link. */
               if FromSet = a context then return fi
                /* all items shifting an S now are right-cplt */
                /* check if they are left-complete */
               for each Item N::=α•Sβ in FromSet do
                    CompleteToLeft :=
                         shifts_to_complete(Item,direction^-1)
                    for each ShiftToComplete in CompleteToLeft do
                         add_shift_possibility
                              (Self,N,ShiftToComplete.endset,
                              'no_alternative')
                          /* alternative not clear: a part of the
                          /* parse has been invented implicitly */
                    od
               od
          elseif FromSet = a context then
               for each DottedRule N::=αS•β with N::=αSβ a
                    production of G
               do add(Self,DottedRule) od
          else
                /* normal case: check if new links caused */
               Items := all items in FromSet having a dotted rule
```

```
                    with • directly at direction of a symbol≈S
                for each Item in Items
                do shift(Self,Item,ShiftPoss) od
            fi
        fi
```

shift: we only call it for shift possibilities between two normal sets. Therefore, it stays the same.

shifts_to_complete: Now, we also need to check for shift possibilities to a context that can replace a normal link. In stead of ShiftsToComplete=Ø we set

```
if there is a shift possibility between Direction context
     and Item.itemset
then ShiftsToComplete := a set containing
          a shift-to-complete-object with shiftlist=empty list,
          endset=Direction context.
else ShiftsToComplete := Ø
fi
```

decide_result: stays the same.

make_context: stays nearly the same, but no context set has to be made.

What do we gain? In shifts_to_complete, we can stop following links when we find a shift possibility to the context, in stead of going on following arrows. But since the search path along the arrows does not split any more in the context, and the usual grammar rules are not very long, the gain seems marginal.

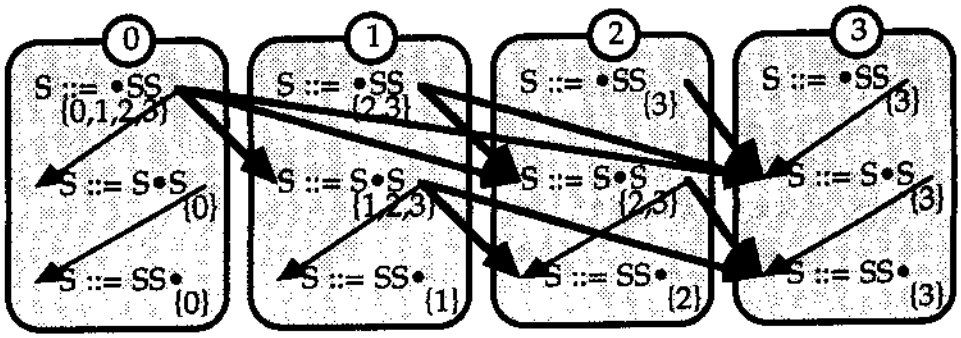
Something can be gained from add_shift_possibility, because we can precompute which items can use a certain shift possibility. But if in the old situation the items are sorted on the symbol that they want to shift, the same gain can be archived there.

Concluding, this algorithm will be slightly faster, but the gain is not very high.

Efficient parse tree storage

We expect the following optimization to give better improvements of the performance. As noted before, our way of storing parse trees may need exponential *space* (our algorithm runs in exponential time in that case). We made another way to store parse trees, such that parse trees always fit in space $O(n^3)$.

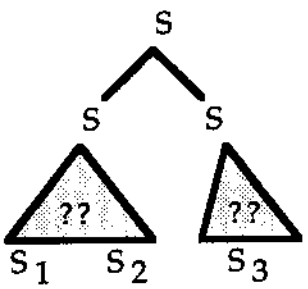
The idea is to annotate at each item the sets that contain linked left- and right-complete items. In an example picture, this looks like (a). In this picture, only the sets containing right-complete items are annotated. The left-complete items can be annotated at each item in the same way.



(a)

When we make a new link, this data has to be updated. This can be done as follows: all items at the left side of the new link now also can reach the right-complete items of item B directly at the right of the link, so we pass the sets containing a right-complete item (these are annotated in B) to the left. The same holds for the items at the right side of the link, which can also reach the left-complete items annotated at the item directly at the left of the new link.

How can we derive a parse tree from this annotation? Take the picture of (a). If we want a parse tree for S that covers all input symbols, we start looking for an item S::=•α in set 0 that promises to reach set 3 (has 3 in its annotated sets). In our case, only S::=•SS can be chosen, but if there are more possibilities, we have an ambiguity. So we choose S::=•SS. Now,we want to find a way to reach set 3. Therefore, we check which items at the other side of outgoing links still promise to reach set 3. In our case, the items S::=S•S in 1,2 and 3 do so. We choose one of these, say the one in 2. This item still is not right-complete, so we again check which links can be followed. This time, only one link brings us to an item reaching set 3 (the S::=SS• in 3), so we have no real choice. We follow that link, and are in a right compete item, so we are ready. But with following the links, we did not yet reconstruct the subtrees, in a picture, we have found a parse tree like (b).



(b)

The ?? trees are unknown parts of the tree. But we can be sure that these parts exist, otherwise the S::=•SS would not have these links. So the ?? trees can be reconstructed in the same way as the main tree. The left tree is reconstructed by looking for an S::=•α in set 0 that promises to reach set 2, the right tree by looking for an S::=•α in set 2 that promises to reach set 3.

With this idea, its gets harder to reconstruct a parse tree from the data structure. Producing a non-leaf node in the tree may take O(n|G|) work, in very ambiguous grammars. But this seems much better then exponential space storage of the trees. Maybe the work for each non-leaf node can be lowered by not only annotating which sets can be reached, but also along which links they can be reached.

With this notation, we don't really need shift possibilities, since we can easily see what shift possibilities exist for S by looking at S::=•α items.

8 A more efficient implementation

Definitions

This chapter contains a specification and an implementation that realizes a more efficient way to store parse trees. The idea was described in the last section of the previous chapter.

For convenience, we define the $\twoheadrightarrow_{direction}$ relation, similar to the $\Rightarrow$ relation:

$$\text{Item} \twoheadrightarrow_{right} \text{Item}' \Leftrightarrow \text{Item} \twoheadrightarrow \text{Item}'$$
$$\text{Item} \twoheadrightarrow_{left} \text{Item}' \Leftrightarrow \text{Item}' \twoheadrightarrow \text{Item}$$

In the brief description that we gave in chapter 7 for efficient parse tree storage, we already saw that each item directly maintains the sets containing uplinked left- and right-complete items. For a specification, it seems more convenient to make a kind of relation. Therefore, we define a relation $\hookrightarrow_{direction}$:

$\text{Item} \hookrightarrow_{right} \text{Itemset} \Leftrightarrow \exists \text{Item}'$ with dotted rule $N=\alpha\bullet$ in Itemset: $\text{Item} \twoheadrightarrow^{*} \text{Item}'$
$\text{Item} \hookrightarrow_{left} \text{Itemset} \Leftrightarrow \exists \text{Item}'$ with dotted_rule $N=\bullet\alpha$ in Itemset : $\text{Item}' \twoheadrightarrow^{*} \text{Item}$

Note that the $\hookrightarrow_{left}$ relation is equivalent to the links Earley makes. The $\hookrightarrow_{right}$ is the equivalent relation for right to left parsing. Making shift possibilities seems waste of time, since we know that there is a shift possibility for N between A and B if and only if there is an Item with dotted rule $N=\bullet\alpha$ in A with Item $\hookrightarrow$ B. Therefore, we remove the shift possibilities from the scenery.
With the $\hookrightarrow$ relation, it is easy to reconstruct a parse tree from the parser situation itself, as shown in the example of chapter 7.

We don't make shift possibilities, and no alternative-objects, which was what we aimed for. Because of this, we also do not need to remember for each link how it was made. But then, a link would only consist of a left and a right side. In this case, we can also make the link directly, in stead of making a special link object.
There are at most $|G|$ items, and at most n $\hookrightarrow$ links from each item, so there are at most $n|G|$ links to be checked when we look for a shift possibility. Since there are $O(n^2|G|)$ shift possibilities in the old situation, this is an improvement.

A problem is caused by removing the shift possibilities: we can not notate a terminal shift possibility explicit.Therefore, we need to handle the shift of terminals implicit.

A Specification

With these relations, we can specify the new parser actions as follows. As in the previous parser, new items can only be added to Outermost.

```
new (Grammar)
     start in an empty situation
     Direction := 'right'
     G := Grammar    /* for later reference to G */
     L := make a context set
     Outermost := a new itemset at right side of L
     add all possible dotted rules of G to Outermost
     add_shift(L,𝒯)

extend (X1..Xn,Direction,TopNonterminal)
     set_direction(Direction)
     for 1≤k≤n with k counting in Direction do
          U := Outermost
          Outermost := a new Direction-most 'normal' itemset
          add_shift(U,Xk)
          while an action is possible do action od
     od
     return decide_result(TopNonterminal)
```

The actions are as follows. They are mainly concerned in making new links/relations between items.

```
shifter /* U is an arbitrary set */
     if ∃Item in set U with wants_to_shift(Item.dotted rule)=S
     and ∃UsefulItem in U
          with dotted rule 'S::=α' with • at Direction^-1
          and UsefulItem ⇨Direction Outermost
     then shift(Item) fi

completer /* now only passes the ⇨ relation */
     if ∃dir,Item,Item',Itemset
     with Item ⇛dir Item' and Item' ⇨dir ItemSet
     then Item ⇨dir ItemSet fi

predictor
     if ∃Item in Outermost with wants_to_shift(Item.dotted_rule)=N
     and N::=γ is production of G
     then add('N::=γ' with • at Direction^-1) fi

wants_to_shift(DottedRule)      /* help function */
     return the symbol at the Direction side of •
                in DottedRule, or ε if there is no such symbol

shift(Item)     /* shift an item to outermost */
     ShiftedItem :=
          add(Item.dotted_rule with • moved 1 symbol to Direction)
     Item ⇛Direction ShiftedItem
```

```
add_shift(FromSet,S)
     for each Item in FromSet
     with wants_to_shift(Item.dotted_rule)≈S
     do shift(Item) od
     while an action is possible do action od

add (N::=α•β)
     Item := find an item with dotted rule N::=α•β in Outermost
     if Item not found
     then add Item with dotted rule N::=α•β to Outermost
          if α=ε then Item ⇨left Outermost fi
          if β=ε then Item ⇨right Outermost fi
     fi
     return Item

set_direction(Dir) /* set new Dir */
     if not Dir-most itemset is a normal set then
          /* watch out! the variable Dir≠Direction! */
          add a Direction-most context set if not yet present
          remove_context(Dir)
          Outermost := Direction-most itemset
          Direction := Dir
     fi

remove_context(Side) /* remove Side context */
     for each Item in Side context
     do retract all Item ⇛Side^-1 Item' relations od
      /* This implies retraction of ⇨ relations! */
     remove Side context

decide_result(S)
     U0 := lefmost normal set
     Un := rightmost normal set
     if there is an Item in U0 with dotted rule S ::= •α
     and Item ⇨right Un
     then return select_a_tree(Item)
     else /* no accept. Find tree that uses some context */
          make a direction-most context set
          L := left context set
          R := right context set
          if  there is an Item in L
          with (L ⇨right Un or L ⇨right R)
          or there is an Item in U0 with Item ⇨right R
          then return 'more-context'
          else return 'failure' fi
     fi
```

An implementation

Preventing double work gets harder because we dropped the shift possibilities. When add_shift is called, we need to find out if the shift between FromSet and outermost for S was made before, to prevent shift from adding a link twice, and to prevent

duplication of work. We can *not* find out about it by checking all the items in FromSet of the form S::=•α (in the left-to-right case) whether they have a ⇨ link to Outermost. The reason is that the creation of such a link *causes* a call to new_shift. We also cannot find out by looking for items of the form N::=α•Sβ in FromSet, whether they have a ⇒ link to some item in outermost. If this is the case, new_shift was called before, but it is possible that shift already has been called, but no such link has been made yet. This can be the case if add_shift has to add another item before it can make the link, and the add of that other item causes another call to shift. To solve the problem, we temporary store the shifts that are done to the context set. When a new outermost set is created, we can forget the old shifts that are done, because only actions on the outermost set are allowed. The shifts made since the last creation of an outermost set are stored in the 'created_shifts' field of ParserObject. In Chapter 9, a Lisp implementation is given.

```
object 'ParserObject':
      itemsets          /* a list of our itemsets */
      direction         /* the direction we're currently working in */
      outermost         /* the direction-most itemset=the only changing set */
      G                 /* the grammar */
      created_shifts    /* list of tuples of the form <FromSet,ShiftedSymbol> */

object 'itemset':
      items             /* a set of items */
      type              /* 'normal' or 'context' */

object 'ends':
      left
      right

object 'item'
      dotted_rule
      links             /* the links we have, an ends-object */
      completes         /* ends-object: the sets with uplinked x-complete items */
      itemset           /* the itemset this item is in */
```

We have the two following methods for parsing:

```
new (Grammar)
      Self := a new ParserObject, with G=Grammar, direction='right',
            itemsets=empty list
      L := add_context(Self)
      new_outermost_set(Self)
      add_dotted_rules(Self)
      add_shift(Self,L,T)
      return Self

extend (Self,X1..Xn,Direction,Symbol)
      set_direction(Self,Direction)
      for 1≤k≤n with k counting in Direction do
            U := outermost
            new_outermost_set(Self)
```

```
        add_shift(Self,U,X_k)
    od
    return decide_result(Self,Symbol)
```

Other functions we need are as follows. We use the same conventions as in the previous algorithms.

```
add_shift (Self,FromSet,S)
     /* prevent double work */
    if there is a <FromSet,Symbol> tuple in created_shifts
    with Symbol≈S then return fi
    add <FromSet,S> to created_shifts
    Items := set containing all Items in FromSet.items
         with wants_to_shift(Item.dotted_rule,direction)≈S
    for each Item in Items do shift(Self,Item) od

shift (Self,Item)
     /* shift does not check for existing links */
     /* So only call when the link does not yet exist */
    ShiftedItem := add(Item.dotted_rule with • moved 1 symbol
                                    to direction)
    add ShiftedItem to Item.links.direction
    add Item to ShiftedItem.links.direction^-1
    complete(Self,Item,ShiftedItem.completes.direction,direction^-1)
    complete(Self,ShiftedItem,Item.completes.direction^-1,direction)
```

Complete passes completes-data to uplinked items. When a direction^{-1}-complete item gets ReallyNew complete sets, add_shift is called to process the new 'shift possibility'.

```
complete(Self,Item,NewCompleteSets,PassDirection)
     /* ReallyNew := completes that are new for this item */
    ReallyNew := NewCompleteSets - Item.completes.PassDirection^-1
    if ReallyNew=Ø then return fi
    add ReallyNew to Item.completes.PassDirection^-1
    DottedRule := Item.dotted_rule
    if wants_to_shift(DottedRule,direction^-1)=ε then
          /* then we made a new shift possibility */
         add_shift(Self,Item.itemset,
              nonterminal produced by DottedRule)
    else
         for each LinkedItem in Item.links.PassDirection
         do complete(Self,LinkedItem,ReallyNew,PassDirection) od
    fi

add (Self,DottedRule)
     Item := find an item with dotted_rule=DottedRule
         in outermost.items
     if Item not found then
         Item := a new item-object, with dotted_rule=DottedRule,
              links=new ends-object with left=right=Ø,
              completes=a new ends-object with left=right=Ø,
              itemset=outermost
         add Item to outermost.items
         if wants_to_shift(DottedRule,direction^-1)=ε
         then Item.completes.direction^-1 := {outermost} fi
```

```
            /* Now do possible actions */
            S := wants_to_shift(DottedRule,direction)
            if S≠ε then
                if S is a nonterminal then
                    /* terminals are handled implicit */
                    /* check if Item can shift its nonterminal */
                    if find_shift(outermost,S,
                        outermost,direction)≠ε
                    then shift(Self,Item) fi
                    /* do predict actions */
                    for each S::=γ in G do
                    do add(Self,S::=γ with • at direction^-1) od
                fi
            else
                complete(Self,Item,{outermost},direction^-1)
            fi
        fi
        return Item

set_direction (Self,Direction)
        if not Direction-most itemset of itemsets is 'normal' then
            make_context(Self)
            remove_context(Self,Direction)
            outermost := Direction-most itemset of itemsets
            direction := Direction
        fi

remove_context (Self,Side)
        Context := Side-most itemset of itemsets
        for each Item in Context.items do
            for each LinkedItem in Items.links.Side^-1 do
                uncomplete(LinkedItem,Context,Side)
                remove Item from LinkedItem.links.Side
            od
        od
        remove Context from itemsets

uncomplete (Item,Context,Side) /* retract context annotations */
        if Context ∈ Item.completes.Side then
            remove Context from Item.completes.Side
            for each LinkedItem in Item.links.Side^-1
            do uncomplete(LinkedItem,Context,Side) od
        fi

new_outermost_set (Self)
        outermost := a new itemset with items=∅, type='normal'
        Self.created_shifts := ∅
        add outermost at direction side of itemsets
        return outermost

add_dotted_rules(Self) /* add all dotted rules to outermost */
        for each possible DottedRule of G do add(Self,DottedRule) od
```

```
add_context(Self)
     Context := new_outermost_set(Self)
     Context.type := 'context'
     add_dotted_rules(Self)
     add_shift(Self,Context,?)
     return Context

make_context (Self) /* make direction-most context if not present */
     if outermost.type = 'context'
     then  return
     else Un := outermost
          add_context(Self)
          add_shift(Self,Un,T )
     fi

decide_result(Self,S)
     U0 := lefmost normal set in itemsets
     Un := rightmost normal set in itemsets
     Item := find_shift(U0,S,Un,'right')
     if Item≠nil
     then return select_a_tree(Self,S)
     else /* no accept. Find tree that uses some context */
          make_context(Self)
          L := left context set
          R := right context set
          if find_shift(L,?,Un,'right')≠nil
          or find_shift(L,?,R,'right')≠nil
          or find_shift(U0,?,R,'right')≠nil
          then return 'more-context'
          else return 'failure' fi
     fi

find_shift (StartSet,S,EndSet,Direction)
      /* find an S-producing item in StartSet that can reach */
      /* Destination in Direction, or nil if no such Item exists */
     if there is an Item in StartSet
     with dotted_rule 'N=α' with • at Direction-1 and N≈S
     and EndSet ∈ Item.completes.Direction
     then return Item
     else return nil fi
```

9 An implementation in Lisp

LeLisp introduction

This chapter contains an implementation of the algorithms given in this theses. The algorithms are written in LeLisp [L90]. This Lisp dialect has a number of features that differ from normal Lisp. We will explain these differences first. A semicolon (';') indicates that the rest of the sentence is no Lisp code but a comment, e.g.

```
; this is an island parser.

(defvar #:sys-package:colon 'ParserObject)
```

causes all atoms starting with a colon (:) being prefixed by '#:ParserObject'. This way, it is easy to prevent name clashes with other modules.

```
(defstruct :ends left right)
```

This is a definition of a **data structure**, similar to a Pascal record. This example defines an ends-object containing a field named 'left' and a field named 'right'. These fields are typeless. We call an instantiation of such a data structure an **object**.

LeLisp has the following functions to **manipulate** objects. An object of type ends can be created with `(omakeq :ends)`. It is possible to initialize the fields immediately. For example, we can put an ends-object in a variable named 'Link', with the left field initialized to 1, and the right field initialized to 2, in the following way:

```
(setq Link (omakeq :ends left 1 right 2))
```

A field is read from an object by send-ing the field name to the object, as follows:

```
(send 'left Link)
```

A field can be changed into new value by providing that value as third parameter:

```
(send 'left Link 8)
```

It is also possible to call a function with the send function. For example

```
(send 'shift AParserObject AnItem)
```

results in the following function call (AParserObject is of type #:ParserObject, which is prefixed to the 'shift' function):

```
(#:ParserObject:shift AParserObject AnItem)
```

If provided, the user-defined 'prin' functions are used for printing an object.

Some functions that might be LeLisp specific:

`(mapcar Function List)`

applies Function on each element in List, and returns the resulting list.

`(any Function List)`

does the following: if there is an Item in List for which Function applied to Item is not nil, that Item is returned. If such an item does not exist, nil is returned.

`(progn` s_1 .. s_n`)`

evaluates the expressions s_1 .. s_n in sequence, and returns the value of s_n.

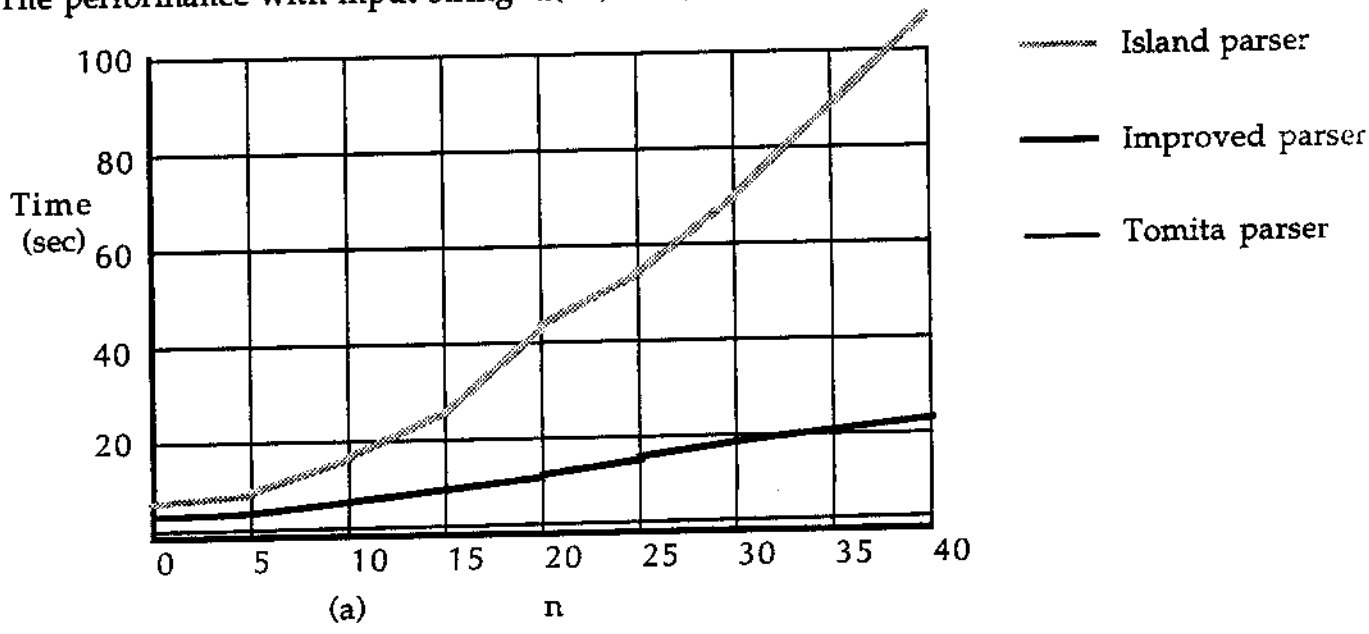
We have halved the formats of the code, to save paper. Island parser is the first version of the island parser. Improved island parser is the implementation of the version of chapter 8. Help functions and Grammar functions are used by both parsers.

Performance

In this section, we give some performance comparisons. The lisp code was not compiled. We used the Tomita parser of the ASF+SDF system [R92] for comparison. The code for this system is compiled, so the comparison is not very fair. But the difference will be a constant factor, so it gives some indication.
The first grammar is:

E ::= T | E + T
T ::= P | T * P
P ::= a

The performance with input string $a(+a)^{n*}a$ (n some natural) is (a):



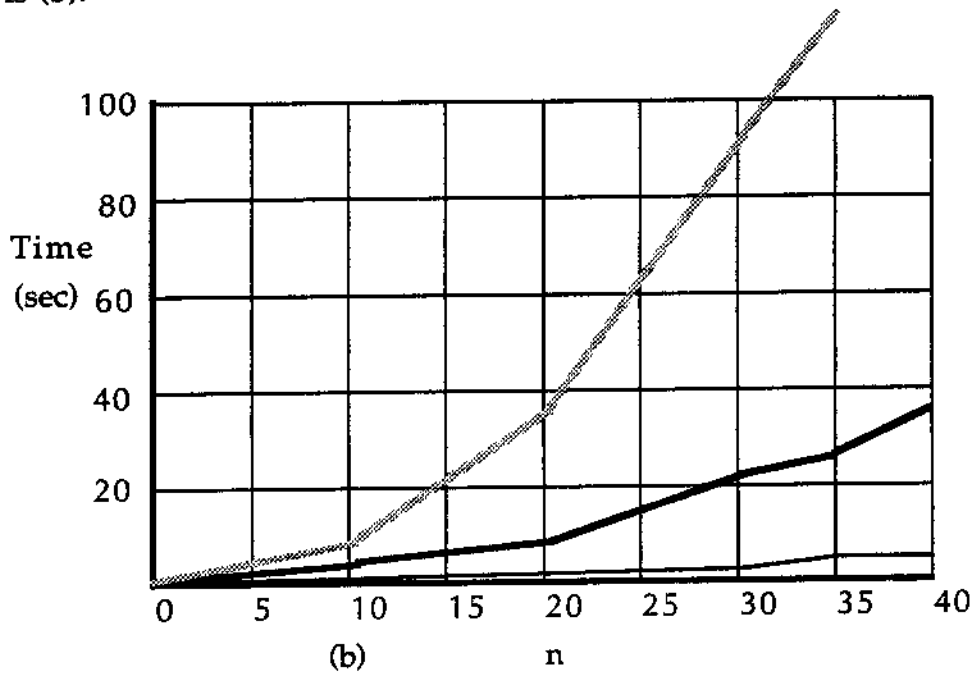
(a)

The next grammar is:

A ::= x | x A x

The input string is x^n with n odd.

The result is (b).

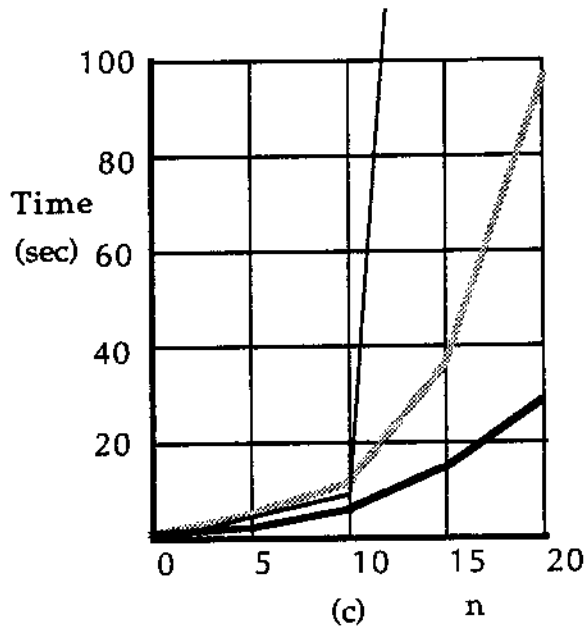


Take the grammar:

A ::= x | A A

Again, the input string is x^n.

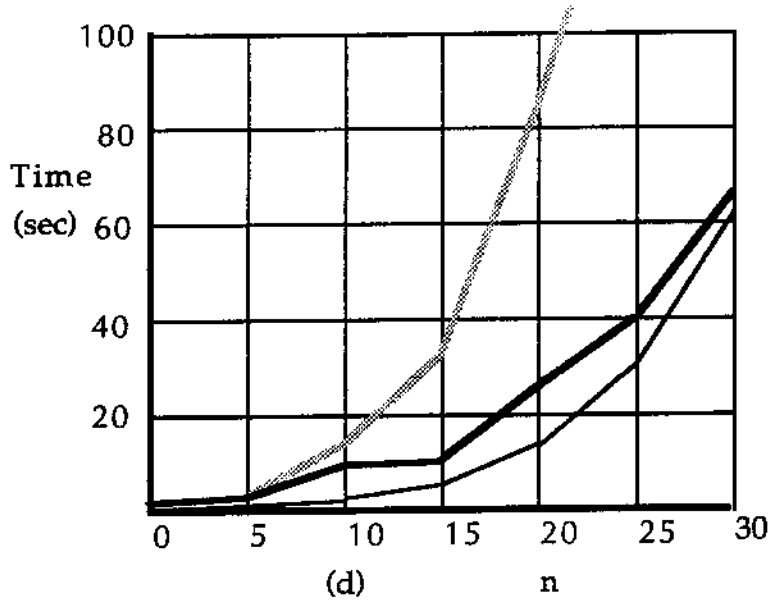
The performance is picture (c). Note the sharp edge in the performance of the Tomita parser. We can not explain this.



Now, we take the grammar

A ::= A A | x | ε

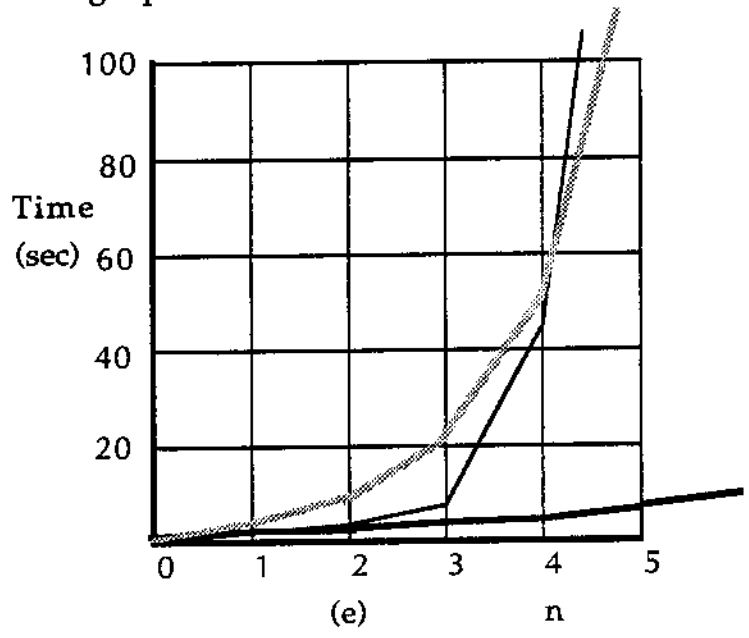
With input string x^n. We get picture (d):



The last grammar we take has a very high ambiguity:

A ::= A A A A A A A A A | x | ε

With input string x^n we get picture (e):



Although these grammars are not practical, they give an impression of the strengths and weaknesses of our parsers. Our parser performs the worst in comparison with Tomita when simple grammars are used. The difference is about a factor 10. Maybe the compiler can improve the performance this much. The higher the ambiguity, the more efficient is our improved parser.

Island parser

```
; an implementation of an island parser..
; Wouter Pasman, 020791.

( defvar #:sys-package:colon 'ParserObject)

;******************OBJECTS****************

( defstruct :ParserObject
  itemsets
  outermost
  shift_possibilities
  G
  direction
  id_count                    ; additional, for generating id's
)

( defstruct :itemset
  print_id                    ; an id to ease printing
  items
  type
)

( defstruct :ends
  left
  right
)

( defstruct :item
  dotted_rule
  links
  itemset
  mark                        ; for remove_useless
)

( defstruct :link
  arrow
  shift_possibility
)

( defstruct :shift_possibility
  symbol
  sets
  alternatives
  mark                        ; for remove_useless
)

( defstruct :alternative
  production
  shifts
)

;****************PRINTING  FUNCTIONS  ***************

( de :ParserObject:prin (self)
  ( print "  IslandParser:" )
  ( mapcar 'print (send 'itemsets self))
  ( print "  Shift Possibilities:")
  ( mapcar 'print (send 'shift_possibilities self))
  ( print (send 'G self))
  ( print "outermost=" (:saveprin_id (send 'outermost self)))
  ( print "direction=" (send 'direction self))
)

( de :itemset:prin (self)
  ( print (send 'type self) " itemset " (:saveprin_id self) )
  ( mapcar 'print (send 'items self))
)

( de :saveprin_id (self) (if (eq self nil) "?" (send 'print_id self)))
 ; checks if object has an id. if not, ? is printed

( de :shift_possibility:prin (self)
  ( prin
    "<" ( :saveprin_id  (send 'left (send 'sets self)) )
    " " (send 'symbol self) " "
    ( if (send 'mark self) "+" "-")
    ( :saveprin_id  (send 'right (send 'sets self)) ) ">"
))

( de :item:prin (self)
  ( prin
    " <-"
   ( mapcar
     ( lambda (Link)
       ( :saveprin_id (send 'itemset (send 'left (send 'arrow Link))))
     )
      ( send 'left (send 'links self))
    )
    ( send 'dotted_rule self)
    ( if (send 'mark self) "+" "-")
   ( mapcar
    ( lambda (Link)
       ( :saveprin_id (send 'itemset (send 'right (send 'arrow Link))))
    )
     ( send 'right (send 'links self))
   )
   "-> "
))

( de :link:prin (self)
  ( prin "link from "
    ( send 'dotted_rule (send 'left (send 'arrow self)))
    "in "
    (:saveprin_id (send 'itemset (send 'left (send 'arrow self))))
    " to "
    (:saveprin_id (send 'itemset (send 'right (send 'arrow self))))
))

( de :PrintTree (ShiftPoss) (:print_tree ShiftPoss 0) )
 ; PrintTree randomly selects a tree from the cyclic parse forest
 ; and prints it. If there is an infinite ambiguity, the PrintTree
 ; may not terminate...
 ; it is only an extra function, to attempt to view the parse forest

( de :print_tree (ShiftPoss Indentatie)
 ; help function to process Indentation
  ( let (Alternatives Alternative)
   ( print
    ( makestring (* 2 Indentatie) 32)
    (send 'symbol ShiftPoss)
   )

    ( setq Alternatives (send 'alternatives ShiftPoss))
    ; we are not interested in ? shift possibilities
    ( if (neq (send 'symbol ShiftPoss) '?)
     ( progn
       ; select at random an alternative and print its shifts
       (setq Alternative (nth (random 0 (length Alternatives)) Alternatives))
       ( if (neq Alternative 'no_alternative)
       ( mapcar
         ( lambda (Shift) (:print_tree Shift (1+ Indentatie)))
         ( send 'shifts Alternative)
    ) )))
)))

;************************METHODS*********************

( de :new (Grammar)
  ( let (L U0 Self)
    ( setq Self
     ( omakeq :ParserObject
       G Grammar direction 'right
       outermost U0
       id_count 100
       itemsets nil
    ))
    ( setq L (:add_context Self))
    ( setq U0 (:new_outermost_set Self))
    ( :add_dotted_rules Self)
    ( :add_shift_possibility Self '?T L 'no_alternative)
   Self
))

( de :extend (Self Text Direction Symbol)
  ( :set_direction Self Direction)
  ( let (Range U)
    ( if (eq Direction 'right)
      ( setq Range (range 1 (length Text)))
      ( setq Range (range (length Text) 1))
    )
    ( foreach Range
      ( lambda (k)
        ( setq U (send 'outermost Self))
        ( :new_outermost_set Self)
        ( :add_shift_possibility Self (nth (1- k) Text) U 'no_alternative)
 )))
  ( :decide_result Self Symbol)
)

;******************OTHER  FUNCTIONS******************

( de :inv (Direction) (if (eq Direction 'left) 'right 'left))

( de :newid (self)
  ( send 'id_count self (1+ (send 'id_count self)))
)

( de :new_outermost_set (Self)
 ; returns new Dir-most set
  ( let (NewSet ItemSets)
    ( setq NewSet
      ( omakeq :itemset items nil type 'normal
        print_id (concat 'I (:newid Self))
    ))
    ( setq ItemSets (send 'itemsets Self))
    ( send 'outermost Self NewSet)
    ( send 'itemsets Self
```

```
    ( if (eq (send 'direction Self) 'right)
      ( append1 ItemSets NewSet)
      ( cons NewSet ItemSets)
    ))
    NewSet
))

( de :add_dotted_rules (Self)
 ; put all dotted rules in outermost set
  ( foreach
    ( send 'dotted_rules (send 'G Self))
    ( lambda (DottedRule) (:add Self DottedRule))
))

( de :add_context (Self)
 ; add_context adds a new outermost context set
 ; returns that set
  ( let ((Set (:new_outermost_set Self)))
    ( :add_dotted_rules Self)
    ( send 'type Set 'context)
    ( :add_shift_possibility Self '? Set 'no_alternative)
   Set
))

( de :direction-most (ItemSets Direction)
 ; returns the direction-most set
  ( if (eq Direction 'right) (lastq ItemSets) (car ItemSets) )
)

( de :find_item (ItemList DottedRule)
 ; check if item with DottedRule is in ItemList
  ( any
    ( lambda (Item)
      ( if ( equal (send 'dotted_rule Item) DottedRule)
        Item
        nil
    ))
    ItemList
))

( de :append_at (Side List Elt)
  ( if (eq Side 'right)
    ( append1 List Elt)
    ( cons Elt List)
))

;************************HELP  FUNCTIONS*********************

( de :set_direction (Self Direction)
  ( let
    ( OtherItem
      ( InvDir (:inv Direction))
      ( Set (:direction-most (send 'itemsets Self) Direction))
    )
    ( if
      ( eq 'normal (send 'type Set))
      nil ; do nothing, Set is normal
      ( progn
        ( :make_context Self) ; make_context if set not already present
        ; Set := the wrong sided context set
        ( setq Set (:direction-most (send 'itemsets Self) Direction))
        ; start with removing links to Set
        ( foreach (send 'items Set)
          ( lambda (Item)
            ( foreach (send InvDir (send 'links Item))
              ( lambda (Link) (:remove_link Link))
      )))
        ; remove shifts to Set
        ( send 'shift_possibilities Self
          ( filter (send 'shift_possibilities Self)
            ( lambda (Shift) (neq (send Direction (send 'sets Shift)) Set))
        ))
        ; remove the context set from the list of sets..
        ( send 'itemsets Self (remq Set (send 'itemsets Self)))

        ( send 'direction Self Direction)
        ( send 'outermost Self
          ( :direction-most (send 'itemsets Self) Direction)
)))))

( de :remove_link (Link)
 ; removes a link, that is the pointers that are to this link
 ; easy, since a link has pointers to the items that have a link to the link
  ( let
    ( ( LeftItemLinks (send 'links (send 'left (send 'arrow Link))))
      ( RightItemLinks (send 'links ( send 'right (send 'arrow Link))))
    )

    ( send 'right LeftItemLinks (remq Link (send 'right LeftItemLinks)))
    ( send 'left RightItemLinks (remq Link (send 'left RightItemLinks)))
    ; now, no pointers exist to Link. It will be removed by the g.c.
))


( de :predictor (Self N)
  ( foreach (send 'predict_rules (send 'G Self) N (send 'direction Self))
    ( lambda (DottedRule) (:add Self DottedRule))
))
```

```
( de :add (Self DottedRule)
 ( let
  ( Item Alt S UsableShifts
    ( Outermost (send 'outermost Self))
    ( Direction (send 'direction Self))
  )
  ( setq Item (:find_item (send 'items Outermost) DottedRule))
  ( if (eq Item nil)
   ( progn
    ( setq Item
       ( omakeq :item dotted_rule DottedRule itemset Outermost
         links (omakeq :ends left nil right nil)
    ))
     ( send 'items Outermost (cons Item (send 'items Outermost)))
     ( if (send 'is_empty DottedRule)
     ( progn
      ( setq Alt
         ( omakeq :alternative production (send 'remove_dot DottedRule)
        shifts nil
      ))
        ( :add_shift_possibility Self (send 'nonterminal DottedRule)
        Outermost Alt
      ))
      ( progn
        ( setq S (send 'wants_to_shift DottedRule Direction))
       ( if (neq S nil)
        ( progn
         ( setq UsableShifts
           ( filter (send 'shift_possibilities Self)
           ( lambda (ShiftPoss)
            ( and
              ( match (send 'symbol ShiftPoss) S)
              ( eq (send (:inv Direction) (send 'sets ShiftPoss))
               Outermost
          )))))
         ( foreach UsableShifts
           ( lambda (ShiftPoss) (:shift Self Item ShiftPoss))
         )
          ( if (is_nonterminal S) (:predictor Self S))
      )))
  )))
  Item
))

( de :get_shift (Self S Left Right)
 ; find one shift between Left and Right for S
 ( any
  ( lambda (ShiftPoss)
   ( if
    ( and
     ( eq (send 'left (send 'sets ShiftPoss)) Left)
     ( eq (send 'right (send 'sets ShiftPoss)) Right)
     ( match (send 'symbol ShiftPoss) S)
    )
    ShiftPoss
    nil
  ))
   ( send 'shift_possibilities Self)
))

( de :add_shift_possibility (Self S FromSet Alternative)
 ( let
  ( ( Ends (omakeq :ends))
    ( Direction (send 'direction Self))
    ShiftPoss Items
  )
  ( send (:inv Direction) Ends FromSet)
  ( send Direction Ends (send 'outermost Self))
  ( setq ShiftPoss
    ( :get_shift Self S (send 'left Ends) (send 'right Ends))
  )
  ( if (neq ShiftPoss nil)
    ( send 'alternatives ShiftPoss
      ( cons Alternative (send 'alternatives ShiftPoss))
    )
    ( progn
     ( setq ShiftPoss
       ( omakeq :shift_possibility
         symbol S sets Ends alternatives (list Alternative)
     ))
      ( send 'shift_possibilities Self
        ( cons ShiftPoss (send 'shift_possibilities Self))
     )
     ( setq Items
       ( filter (send 'items FromSet)
       ( lambda (Item)
        ( match
          ( send 'wants_to_shift (send 'dotted_rule Item) Direction)
         S
     ))))
      ( foreach Items (lambda (Item) (:shift Self Item ShiftPoss)) )
))))


( de :shift (Self Item ShiftPoss)
 ( let
   ( L Links ToComplete ShiftedRule NewItem Production Symbol From Alternative
    ( Dir (send 'direction Self))
    ( InvDir (:inv (send 'direction Self)))
```

```
    ( Arrow (omakeq :ends))
  )
  ( setq ShiftedRule (send 'shift (send 'dotted_rule Item) Dir))
  ( setq NewItem (:add Self ShiftedRule))
  ( send Dir Arrow NewItem)
  ( send InvDir Arrow Item)
  ( setq L (omakeq :link arrow Arrow shift_possibility ShiftPoss))
  ( setq Links (send 'links (send 'left Arrow)))
  ( send 'right Links (cons L (send 'right Links)))
  ( setq Links (send 'links (send 'right Arrow)))
  ( send 'left Links (cons L (send 'left Links)))
  ( setq ToComplete (omakeq :ends))
  ( send Dir ToComplete
    ( :shifts_to_complete (send Dir Arrow) Dir)
  )
  ( if (eq (send Dir ToComplete) nil)
    nil  ; then return
   ( progn
     ( send InvDir ToComplete
       ( :shifts_to_complete (send InvDir Arrow) InvDir)
     )
      ( setq Production (send 'remove_dot (send 'dotted_rule Item)))
      ( setq Symbol (send 'nonterminal Production))
     ( permute
       ( lambda (LeftToComplete RightToComplete)
        ( if (eq Direction 'right)
          ( setq From (send 'endset LeftToComplete))
          ( setq From (send 'endset RightToComplete))
        )
        ( setq Alternative
          ( omakeq :alternative production Production
          shifts
          ( append
            ( send 'shiftlist LeftToComplete)
            ( list ShiftPoss)
             ( send 'shiftlist RightToComplete)
       )))
         ( :add_shift_possibility Self Symbol From Alternative)
      )
      ( send 'left ToComplete)
      ( send 'right ToComplete)
)))))


( defstruct :shift-to-complete
  shiftlist
  endset
)


( de :shifts_to_complete (Item Direction)
 ( let
    ( ShiftsToComplete ShiftToComplete LinkShift ToCompeteA ShiftsToCompleteA
     ( InvDir (:inv Direction))
  )
   ( if (eq (send 'wants_to_shift (send 'dotted_rule Item) Direction) nil)
   ( progn
     ( setq ShiftToComplete
       ( omakeq :shift-to-complete shiftlist nil
         endset (send 'itemset Item)
     ))
      (list ShiftToComplete)
   )
   ( progn
     ( setq ShiftsToComplete nil)
     ( foreach (send Direction (send 'links Item))
      ( lambda (Link)
        ( setq ShiftsToCompleteA
          ( :shifts_to_complete
           (send Direction (send 'arrow Link))
           Direction
       ))
         ( setq LinkShift (send 'shift_possibility Link))
         ( foreach ShiftsToCompleteA
          ( lambda (ToCompleteA)
            ( send 'shiftlist ToCompleteA
              ( :append_at InvDir (send 'shiftlist ToCompleteA) LinkShift)
       )))
         ( setq ShiftsToComplete (append ShiftsToCompleteA ShiftsToComplete))
     ))
      ShiftsToComplete
))))

( de :firstnormal (ItemSets)
  ; returns first set if it is normal, else the second.
  ( if (eq (send 'type (car ItemSets)) 'normal)
    ( car ItemSets)
    ( cadr ItemSets)
))

( de :decide_result (Self Symbol)
  ( let (U0 Un ItemSets Shift)
    ( setq ItemSets (send 'itemsets Self))
    ( setq U0 (:firstnormal ItemSets))
    ( setq Un (:firstnormal (reverse ItemSets)))
    ( setq Shift (:get_shift Self Symbol U0 Un))
    ; if we found a Shift, then there is a shift poss we need
    ( if Shift
      Shift ; no select_a_tree, just return the shift poss
      ( progn ; check for failure or more-context
        ( :make_context Self)
        ( setq ItemSets (send 'itemsets Self))
       ( setq L (car ItemSets))
       ( setq R (lastq ItemSets))
       ( if
        ( or
          ( :get_shift Self '? L R)
          ( :get_shift Self '? L Un)
          ( :get_shift Self '? U0 R)
        )
         'more-context
         'failure
)))))

( de :make_context (Self)
  ( let ((Un (send 'outermost Self)))
   ( if (eq (send 'type Un) 'context)
     nil ; then return
    ( progn
     ( :add_context Self)
      ( :add_shift_possibility Self '?T Un 'no_alternative)
      ; optional: ( :remove_useless Self)
))))

;*************functions to remove useless items************

( de :remove_useless (Self)
 ( let
   ( L U0 Un R ReverseItemsets
    ( ItemSets (send 'itemsets Self))
    ( Shifts (send 'shift_possibilities Self))
  )
  ( :make_context Self)
  ( foreach ItemSets
   ( lambda (ItemSet)
     ( if (eq (send 'type ItemSet) 'normal)
       ( foreach (send 'items ItemSet) (lambda (Item) (send 'mark Item nil)))
 )))
  ( foreach Shifts (lambda (Shift) (send 'mark Shift nil)))

  ( setq L (car ItemSets))
  ( setq U0 (cadr ItemSets))
  ( setq ReverseItemsets (reverse ItemSets))
  ( setq Un (cadr ReverseItemsets))
  ( setq R (car ReverseItemsets))
  ( foreach Shifts
   ( lambda (ShiftPoss)
    ( if
      ( let ((Sets (send 'sets ShiftPoss)))
       ( and
         ( let ((Left (send 'left Sets)))
          ( or (eq Left L) (eq Left U0))
         )
          ( let ((Right (send 'right Sets)))
           ( or (eq Right R) (eq Right Un))
     )))
      ( :useful ShiftPoss)
 )))
  ( send 'shift_possibilities Self
   ( filter Shifts
     ( lambda (ShiftPoss) (send 'mark ShiftPoss))
  ))
  ( foreach ItemSets
   ( lambda (Uk)
    ( if (eq (send 'type Uk) 'normal)
     ( foreach (send 'items Uk)
      ( lambda (Item)
       ( if
         ( let ((Links (send 'links Item)))
          ( and
            ( eq (send 'mark Item) nil)
           ( or
             ( eq (send 'left Links) nil)
             ( eq (send 'right Links) nil)
         )))
          ( :remove Item)
       ))
))))))

( de :useful (ShiftPoss)
  ( if (send 'mark ShiftPoss)
    nil ; we're not happy with returns in lisp
   ( progn
    ( send 'mark ShiftPoss t)
    ( foreach (send 'alternatives ShiftPoss)
     ( lambda (Alternative)
       ( if (neq Alternative 'no_alternative)
        ( let (( Production (send 'production Alternative)))
         ( foreach (send 'shifts Alternative)
          ( lambda (ShiftPoss) (:useful ShiftPoss))
        )
         ( send 'mark
           ( :find_item (send 'items (send 'left (send 'sets ShiftPoss)))
            ( send 'put_dot_at_start Production 'right)
         )
         t
        )
         ( send 'mark
```

```
            ( :find_item (send 'items (send 'right (send 'sets ShiftPoss)))
              ( send 'put_dot_at_start Production 'left)
            )
            t
          ))
    ))))
))


( de :remove (Item)
 (let
  ( ( Links (send 'links Item))
    ( ItemSet (send 'itemset Item))
  )
  ( foreach (list 'left 'right)
   ( lambda (Side)
     ( let ((InvSide (:inv Side)))
      ( foreach (send Side Links)
       ( lambda (Link)
          ( let ((LinkedItem (send Side (send 'arrow Link))) HisLinks)
           ( setq HisLinks (send 'links LinkedItem))
           ( send InvSide HisLinks (remq Link (send InvSide HisLinks)))
           ( if (eq (send InvSide HisLinks) nil)
             ( :remove LinkedItem)
  )))))))
   ( send 'items ItemSet (remq Item (send 'items ItemSet)))
))
```

Improved island parser

```
; improved island parser, 040791 W.Pasman

( defvar #:sys-package:colon 'ParserObject)

;******************OBJECTS*****************

( defstruct :ParserObject
  itemsets
  direction
  outermost
  G
  id_count
  created_shifts     ; shifts made to outermost set: (FromSet.Symbol)
)

( defstruct :itemset
  items
  type
  id                 ; for reference to sets while printing
)

( defstruct :ends
  left
  right
)

( defstruct :item
  dotted_rule
  links
  completes
  itemset            ; just for print purposes
)


;****************PRINTING  FUNCTIONS  **************

( de :id (AnItemSet) (if (eq AnItemSet nil) '? (send 'id AnItemSet)))

( de :ParserObject:prin (self)
  ( print "  IslandParser:" )
  ( mapcar 'print (send 'itemsets self))
  ( print "outermost=" (:id (send 'outermost self)))
  ( print "direction=" (send 'direction self))
  ( print (send 'G self))
)

( de :itemset:prin (ItemSet)
  ( print (send 'type ItemSet) " itemset " (:id ItemSet) )
  ( mapcar 'print (send 'items ItemSet))
)

( de :item:prin (Item)
 ( prin
  ( mapcar
    ( lambda (OtherItem) (:id (send 'itemset OtherItem)))
    ( send 'left (send 'links Item))
  )
  ( mapcar (lambda (Set) (:id Set)) (send 'left (send 'completes Item)))
  ( send 'dotted_rule Item)
  ( mapcar (lambda (Set) (:id Set)) (send 'right (send 'completes Item)))
  ( mapcar
    ( lambda (OtherItem) (:id (send 'itemset OtherItem)))
    ( send 'right (send 'links Item))
  )
))

( de :PrintResult (Result)
  ( if (eq (type-of Result) 'cons)
    ( let (ItemSets (Self (car Result)) (Symbol (cdr Result)))
      ( setq ItemSets (send 'itemsets Self))
      ( :PrintTree
        (:firstnormal ItemSets) Symbol (:firstnormal (reverse ItemSets)) 0
    ))
    ( print Result)
  )
  nil
)


( de :PrintTree (StartSet Symbol EndSet Depth)
 ; print one of the ways to produce Symbol with symbols between
 ; Start and EndSet
  ( print (makestring (* 2 Depth) 32) Symbol)
   ; if Symbol is terminal, then we cannot produce it.
   ; furthermore, it is not useful to explain how a shift
   ; can be produced in a context
   ( if
    ( or
```

```
    ( not (is_nonterminal Symbol))
    ( and (eq (send 'type StartSet) 'context) (eq StartSet EndSet))
  )
  nil ; so we print nothing more
  ( let (Alternatives Alternative)
  ; else we choose a useful production rule (item)
  ( setq Alternatives
    ( filter (send 'items StartSet)
    ( lambda (Item)
      ( let ((DottedRule (send 'dotted_rule Item)))
      ( and
        ( match (send 'nonterminal DottedRule) Symbol)
        ( eq (send 'wants_to_shift DottedRule 'left) nil)
        ( memberq EndSet (send 'right (send 'completes Item)))
  )))))
   ( setq Alternative (nth (random 0 (length Alternatives)) Alternatives))
   ( :GetToEnd Alternative EndSet Depth)
)))

( de :GetToEnd (Item EndSet Depth)
 ( let
   ( ToShift UsefulLinkedItems ChosenItem
    ( DottedRule (send 'dotted_rule Item))
  )
   ( setq ToShift (send 'wants_to_shift (send 'dotted_rule Item) 'right))
   ; if we are at the end, stop it
   ( if (eq ToShift nil)
    nil
     ; else follow links until we reach right-complete item in EndSet
     ; first find useful links: linked items that promise to reach EndSet
    ( setq UsefulLinkedItems
      ( filter (send 'right (send 'links Item))
      ( lambda (LinkedItem)
        ( memberq EndSet (send 'right (send 'completes LinkedItem)) )
  )))
    ; choose one of these links
   ( setq ChosenItem
     ( nth (random 0 (length UsefulLinkedItems)) UsefulLinkedItems)
   )
    ; and print how the link was made
   ( :PrintTree
     (send 'itemset Item) ToShift (send 'itemset ChosenItem) (1+ Depth)
   )
    ; and print the rest of the links
    ( :GetToEnd ChosenItem EndSet Depth)
)))

;**********METHODS**********

( de :new (Grammar)
 ( let (Self L)
  ( setq Self
   ( omakeq :ParserObject
     G Grammar direction 'right id_count 1 itemsets nil
  ))
  ( setq L (:add_context Self))
  ( :new_outermost_set Self)
  ( :add_dotted_rules Self)
  ( :add_shift Self L '?T)
  Self
))

( de :extend (Self Symbols Direction Symbol)
 ( when Symbols ; check if there is really work to do
  ( let (Range U)
   ( :set_direction Self Direction)
   ( if (eq Direction 'right)
    ( setq Range (range 1 (length Symbols)))
    ( setq Range (range (length Symbols) 1))
   )
   ( foreach Range
    ( lambda (k)
     ( setq U (send 'outermost Self))
     ( :new_outermost_set Self)
     ( :add_shift Self U (nth (1- k) Symbols) )
   ))
   ( :decide_result Self Symbol)
)))

;**********THE REAL WORK**********

( de :add_shift (Self FromSet S)
 ( if
  ( any
   ( lambda (DoneBefore)
    ( and (eq (car DoneBefore) FromSet) (match (cdr DoneBefore) S))
   )
   ( send 'created_shifts Self)
  )
  nil ; return: done before
  ( let (Items (Direction (send 'direction Self)))
   ( :add_elt 'created_shifts Self (cons FromSet S))
   ( setq Items
    ( filter (send 'items FromSet)
    ( lambda (Item)
     ( match S
      ( send 'wants_to_shift (send 'dotted_rule Item) Direction)
    ))))
    ( foreach Items (lambda (Item) (:shift Self Item)))
)))

( de :add_elt (ListField Object Item)
 ; add Item to the Object.ListField
 ( send ListField Object (cons Item (send ListField Object)))
)

( de :rem_elt (ListField Object Item)
 ; remove Item from Object.ListField
 ( send ListField Object (remq Item (send ListField Object)))
)

( de :shift (Self Item)
 ( let
  ( ( direction (send 'direction Self))
    invdir ShiftedItem
  )
  ( setq invdir (:inv direction))
  ( setq ShiftedItem
    (:add Self (send 'shift (send 'dotted_rule Item) direction))
  )
  ; check for debug purposes!
  ( if (memberq ShiftedItem (send direction (send 'links Item)))
   ( error ':shift "shift twice" Item)
  )
  ( :add_elt direction (send 'links Item) ShiftedItem)
  ( :add_elt invdir (send 'links ShiftedItem) Item)
  ( :complete Self
    Item (send direction (send 'completes ShiftedItem)) invdir
  )
  ( :complete Self
    ShiftedItem (send invdir (send 'completes Item)) direction
  )
))

( de :complete (Self Item NewCompleteSets PassDirection)
 ( let
  ( ReallyNew
   ( InvPassDir (:inv PassDirection))
   ( Completes (send 'completes Item))
   ( direction (send 'direction Self))
   ( DottedRule (send 'dotted_rule Item))
  )

  ( setq ReallyNew (subtract (send InvPassDir Completes) NewCompleteSets))

  ( if (eq ReallyNew nil)
   nil ; return
   ( send InvPassDir Completes
    ( append ReallyNew (send InvPassDir Completes))
   )
   ( if
     (eq (send 'wants_to_shift DottedRule (:inv (send 'direction Self))) nil)
     ( :add_shift Self (send 'itemset Item) (send 'nonterminal DottedRule))
    ( foreach (send PassDirection (send 'links Item))
     ( lambda (LinkedItem)
      ( :complete Self LinkedItem ReallyNew PassDirection)
    ))
))))

( de :add (Self DottedRule)
 ( let
  ( ( outermost (send 'outermost Self))
   ( direction (send 'direction Self))
   Item S ItemA invdir
  )
  ( setq invdir (:inv direction))
  ( setq Item (:find_item DottedRule outermost))
  ( when (eq Item nil)
   ( setq Item
    (omakeq :item
     dotted_rule DottedRule
     links (omakeq :ends left nil right nil)
     completes (omakeq :ends left nil right nil)
     itemset outermost
   ))
   ( :add_elt 'items outermost Item)
   ( if (eq (send 'wants_to_shift DottedRule invdir) nil)
    ( send invdir (send 'completes Item) (list outermost))
   )
   ( setq S ( send 'wants_to_shift DottedRule direction))
   ( if (neq S nil)
    ( when (is_nonterminal S)
    ( if
      ( :find_shift outermost S outermost direction)
     ( :shift Self Item)
    )
     ( foreach (send 'predict_rules (send 'G Self) S direction)
     ( lambda (PredictedDR) (:add Self PredictedDR))
   ))
    ( :complete Self Item (list outermost) invdir)
  ))
  Item
))

( de :find_item (DottedRule ItemSet)
```

```
 ( any
   ( lambda (Item)
     ( if (equal (send 'dotted_rule Item) DottedRule)
       Item
       nil
   ))
    ( send 'items ItemSet)
))

( de :set_direction (Self Direction)
  ( when
    ( neq 'normal
      ( send 'type (:direction-most (send 'itemsets Self) Direction))
    )
    ( :make_context Self)
    ( :remove_context Self Direction)
    ( send 'outermost Self (:direction-most (send 'itemsets Self) Direction))
    ( send 'direction Self Direction)
))

( de :remove_context (Self Side)
  ( let (( Context (:direction-most (send 'itemsets Self) Side)))
    ( foreach (send 'items Context)
     ( lambda (Item)
       ( foreach (send (:inv Side) (send 'links Item))
        ( lambda (LinkedItem)
          ( :uncomplete LinkedItem Context Side)
          ( :rem_elt Side (send 'links LinkedItem) Item)
  ))))
    ( :rem_elt 'itemsets Self Context)
))

( de :uncomplete (Item Context Side)
  ( let ((Completes (send 'completes Item)))
    ( when (memberq Context (send Side Completes))
      ( :rem_elt Side Completes Context)
      ( foreach (send (:inv Side) (send 'links Item))
        ( lambda (LinkedItem) (:uncomplete LinkedItem Context Side))
))))


( de :new_outermost_set (Self)
  ( let ((outermost (omakeq :itemset items nil type 'normal id (:newid Self))))
    ( send 'outermost Self outermost)
    ( send 'created_shifts Self nil) ; no shifts made to it right now
    ( send 'itemsets Self
      ( if (eq (send 'direction Self) 'right)
        ( append1 (send 'itemsets Self) outermost)
        ( cons outermost (send 'itemsets Self))
   ))
    outermost
))

( de :add_dotted_rules (Self)
  ( foreach (send 'dotted_rules (send 'G Self))
    ( lambda (DottedRule) (:add Self DottedRule))
))

( de :add_context (Self)
  ( let ((Context (:new_outermost_set Self)))
    ( send 'type Context 'context)
    ( :add_dotted_rules Self)
    ( :add_shift Self Context '?)
   Context
))

( de :make_context (Self)
  ( let ((Un (send 'outermost Self)))
    ( if (eq (send 'type Un) 'context)
      nil
      ( :add_context Self)
      ( :add_shift Self Un '?T)
)))

( de :decide_result (Self S)
  ( let
    ( U0 Un Item L R
      ( ItemSets (send 'itemsets Self))
    )
    ( setq U0 (:firstnormal ItemSets))
    ( setq Un (:firstnormal (reverse ItemSets)))
    ( setq Item (:find_shift U0 S Un 'right))
    ( if (neq Item nil)
      ( cons Self S); no select_a_tree
      ( progn
        ( :make_context Self)
        ( setq L (car ItemSets))
        ( setq R (lastq ItemSets))
        ( if
          ( or
            ( :find_shift L '? Un 'right)
            ( :find_shift L '? R 'right)
            ( :find_shift U0 '? R 'right)
          )
          'more-context
          'failure
)))))

( de :find_shift (StartSet S EndSet Direction)
   ( setq InvDir (:inv Direction))
  ( any
    ( lambda (Item)
      ( let ((DottedRule (send 'dotted_rule Item)))
      ( if
        ( and
          ( match (send 'nonterminal DottedRule) S)
          ( not (send 'wants_to_shift DottedRule InvDir))
          ( memberq EndSet (send Direction (send 'completes Item)))
        )
        Item
        nil
   )))
    (send 'items StartSet)
)))


;*****************MISCELLANEOUS  FUNCTIONS*****************

( de :inv (Direction) (if (eq Direction 'left) 'right 'left))

( de :newid (Self)
  ( send 'id_count Self (1+ (send 'id_count Self)))
)

( de :direction-most (List Direction)
  ( if (eq Direction 'right) (lastq List) (car List))
)

( de :firstnormal (ItemSets)
  ( if (neq (send 'type (car ItemSets)) 'normal)
    ( cadr ItemSets)
    ( car ItemSets)
))
```

Help functions

```
; common functions

( defvar #:sys-package:colon 'CommonFunctions)

;————remove-duplicates————
; removes duplicates from a list.
( de remove-duplicates (List)
 ( if (eq List nil)
   nil
   ( cons (car List) (remove-duplicates (delq (car List) (cdr List))))
))

;————foreach————
 ; for each element x in List do Function(x)
( de foreach (List Function) (mapcar Function List))

;————filter————
 ; filter from a list only that elements e for which TestFunctions(e)=true
( de filter (List TestFunction)
 ( if (eq List nil)
   nil
   ( if (apply TestFunction (list (car List)))
    ( cons (car List) (filter (cdr List) TestFunction) )
    ( filter (cdr List) TestFunction)
)))

;————range————
 ; (:range 3 7) --> (3 4 5 6 7)
 ; (:range 8 3) --> (8 7 6 5 4 3)
( de range (Begin End)
 ( if (eq Begin End)
   (list End)
   ( progn
    ( if (< Begin End)
      ( cons Begin (range (1+ Begin) End))
      ( cons Begin (range (1- Begin) End))
))))

;————memberq————
 ; same as member, but using eq in stead of equal
 ; for recursive structures!!!
( de memberq (s l)
 ( cond
   ( (atom l) ())
   ( (eq s (car l)) l)
   ( t (memberq s (cdr l)))
))

;————to-one-list————
; makes one list from list of lists
; ex: (to-one-list '((1 2 3) (4 5 6) (7 8 9)) ) = (1 2 3 4 5 6 7 8 9)
( de to-one-list (List) (apply 'append List))

;————permute————
 ; permute each member of first list with each of second.
 ; apply f to them.
 ; ex: (permute 'cons '(1 2 3) '(4 5)) =
 ; (((1 . 4) (1 . 5)) ((2 . 4) (2 . 5)) ((3 . 4) (3 . 5)))
( de permute (f l1 l2)
 ( mapcar
  ( lambda (e1)
   ( mapcar
    ( lambda (e2) (apply f (list e1 e2)))
    l2
  ))
  l1
))

;————lastq————
 ; gives last element of a list.
( de lastq (List) (car (last List)))

;————subtract————
 ; subtract set1 from set2
 ; this is remove all items in set1 from set2
( de subtract (Set1 Set2)
 ( if (eq Set1 nil)
   Set2
   ( subtract (cdr Set1) (remq (car Set1) Set2))
))
```

Grammar functions

```
; grammatica definitions, dotted rules etc.

( defvar #:sys-package:colon 'Grammar)

;******************OBJECTS*********************

( defstruct :Grammar
 rules                ; bag (list) of rules
)

( defstruct :rule
 nonterminal          ; the left side of the rule
 production           ; list of (non)terminals
)

( defstruct :dotted_rule
 nonterminal          ; the left side of the rule
 reverse-of-before-dot    ; useful for shifting left
 after-dot            ; a list of (non)terminals
)

;**************SPECIAL  FUNCTIONS***********

( de :print_list_without_brackets (List)
 (mapcar (lambda (x) (prin x " ")) List)
)

( de #:Grammar:Grammar:prin (self)
 ( print "(")
 ( mapcar (lambda (rule) (print " " rule)) (send 'rules self))
 ( print ")" )
)

( de #:Grammar:rule:prin (self)
 ( prin (send 'nonterminal self) " ::= ")
 ( :print_list_without_brackets (send 'production self) )
)

( de #:Grammar:dotted_rule:prin (self)
 ( prin (send 'nonterminal self) " = ")
 ( :print_list_without_brackets (reverse (send 'reverse-of-before-dot self)))
 ( prin " * " )
 ( :print_list_without_brackets (send 'after-dot self))
)

;————is_nonterminal————
( de is_nonterminal (Symbol)
 ( let ((Ascii (car (explode Symbol))))
   ; test whether first char. of Symbol between A and Z
  ( and (>= Ascii 65) (<= Ascii 90))
))

;******************METHODS***************

;————dotted_rules————
 ;gives all rules of Grammar
( de :dotted_rules (Grammar)
 ( to-one-list
  ( mapcar
   ( lambda (rule) (send 'dots rule))
   (send 'rules Grammar)
)))

;————dots————
 ; given a production rule, returns a list of all dotted rules with that
 ; production
( de :dots (Rule)
 ( let
   ( ( Nonterminal (send 'nonterminal Rule))
    ( Production (send 'production Rule))
    Length
  )
  ( setq Length (length Production))
  ( mapcar
   ( lambda (DotPos)
     ( omakeq :dotted_rule nonterminal Nonterminal
      reverse-of-before-dot (reverse (firstn DotPos Production))
      after-dot (lastn (- Length DotPos) Production)
   ))
   ( range 0 Length)
)))

;————predict_rules————
 ; gives all rules that can produce a nonterminal, with dot at start
( de :predict_rules (Grammar Nonterminal Direction)
 ( foreach
```

```
  ( filter
    ( send 'rules Grammar)
    ( lambda (Rule) (eq (send 'nonterminal Rule) Nonterminal))
  )
   ( lambda (Rule) (send 'put_dot_at_start Rule Direction))
))

;----------put_dot_at_start----------
 ; given a Rule, make a dotted rule with dot at start (opposite of Direction)
( de :put_dot_at_start (Rule Direction)
  ( let ((dr ( omakeq :dotted_rule nonterminal (send 'nonterminal Rule))))
   ( if (eq Direction 'right)
    ( progn
      ( send 'reverse-of-before-dot dr nil)
      ( send 'after-dot dr (send 'production Rule))
    )
    ( progn
      ( send 'reverse-of-before-dot dr (reverse (send 'production Rule)))
      ( send 'after-dot dr nil)
  ))
   dr
))

;----------shift----------
 ; shift the dot of the given dotted rule one in Direction
( de :shift (DottedRule Direction)
 ( let
  (
    ( dr (omakeq :dotted_rule nonterminal (send 'nonterminal DottedRule)))
    ( after (send 'after-dot DottedRule))
    ( before (send 'reverse-of-before-dot DottedRule))
  )
   ( if (eq Direction 'right)
    ; shift dot right
    ( progn
      ( send 'reverse-of-before-dot dr ( cons (car after) before))
      ( send 'after-dot dr (cdr after))
    )
    ; shift dot left
    ( progn
      ( send 'reverse-of-before-dot dr ( cdr before))
      ( send 'after-dot dr ( cons (car before) after))
    )
  )
   dr
))

;----------wants_to_shift----------
 ; given a dotted rule, look what symbol can be shift in Direction
 ; if dot at outermost position for Direction,  return nil
( de :wants_to_shift (DottedRule Direction)
  ( if (eq Direction 'left)
    ( car (send 'reverse-of-before-dot DottedRule))
    ( car (send 'after-dot DottedRule))
))

;----------remove_dot-------
 ; converts dotted rule back into a rule
( de :remove_dot (DottedRule)
  ( omakeq :rule
     nonterminal (send 'nonterminal DottedRule)
    production
    ( append
      ( reverse (send 'reverse-of-before-dot DottedRule))
      ( send 'after-dot DottedRule)
)))

;----------is_empty----------
 ;checks if a DottedRule is empty (before dot and after dot both empty)
( de :is_empty (DottedRule)
  ( and
    ( eq (send 'reverse-of-before-dot DottedRule) nil)
    ( eq (send 'after-dot DottedRule) nil)
))


;----------match----------
 ; checks if two symbols match
 ; because we use '? and '?T symbols
( de match (x y)
  ( and (neq x nil) (neq y nil) ; empty must NEVER match
    ( or
      ( eq x y)
      ( eq x '?)
      ( eq y '?)
       ( and (eq x '?T) (not (is_nonterminal y)))
       ( and (eq y '?T) (not (is_nonterminal x)))
)))
```

Index

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Colofon

Technical information

Used hardware:	Macintosh IIci for this thesis Sun 3/60 and 3/140 for the LeLisp implementation
Programs used:	Microsoft Word Version 4.00C MacDraw Version 1.9.5 Le-Lisp Version 15.24
Printer:	Agfa P3400 PS laserprinter
Fonts:	Palentino for normal text and Le-Lisp code Symbol, Zapf Dingbats and Zapf Chancery for some special characters Courier for pseudo pascal code
#Characters:	160208

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Ideas worked out:	4th of February 1991 ... 7th of June 1991
Thesis written:	7th of June 1991 ... August 1991