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Attribute Grammars: A short tutorial Tree-Oriented Programming

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Overview

- Historical overview
- Example
- Concepts
- AG by example
- Discussion

Not covered

- First class aspects
- Delegation
- Subtyping-like systems
- Embedding attribute grammars in other languages
- Extending compilers dynamically

Implementing a language

- Parsing is about syntax
- What about semantics?

Historical Overview

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  - Scope rules
  - Typing rules
  - Pretty printing
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- Context-free grammars have limited expressiveness, and thus fail to describe:
  - Scope rules
  - Typing rules
  - Pretty printing
  - Code generation
- Are there extensions?
- Context-sensitive grammars are not very useful, so the idea came up to...

Parameterize Non-Terminal Symbols

Parameterize non-terminal symbols:

- With strings forming part of their name: *2-level grammars* used for the description of Algol 68 (1973)
- With trees: affix grammars

$$
\begin{array}{lll}
S & \to L\langle N\rangle & \\
N & \to 1:N \mid 0 & \\
L\langle N\rangle & \to A\langle N\rangle \quad B\langle N\rangle \quad C\langle N\rangle & \\
A\langle 0\rangle & \to \epsilon \qquad\qquad B\langle 0\rangle \to \epsilon & \ldots \\
A\langle 1:N\rangle & \to a\ A\langle N\rangle \qquad B\langle 1:N\rangle \to b\ B\langle N\rangle & \ldots
\end{array}
$$

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A\langle 1:N\rangle & \to a\ A\langle N\rangle \qquad B\langle 1:N\rangle \to b\ B\langle N\rangle & \ldots
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$$

- With values from some other domain: *attribute grammars* (Knuth)

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- A lot of research on the efficient evaluation, both in space and time, and
  - So we could write compilers with it that were *almost* as efficient as hand-written compilers

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  - And other people thought it was something for compiler writers only
  - And had do do something very complicated with *grammars*
  - And so they are still largely ignored
- We may see attribute grammars however as:
  - A way to do lazy functional programming in an imperative setting
  - An aspect oriented programming language
  - A domain-specific language for writing *catamorphisms*

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  - *Synthesized* attributes that are used to pass information *upwards*

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- A description of which non-terminals have which attributes:
  - *Inherited* attributes, that are used or passing information *downwards* in the tree
  - *Synthesized* attributes that are used to pass information *upwards*
- For *each production* a description how to compute the:
  - Inherited attributes of the non-terminals in the *right hand side*
  - The synthesized attributes of the non-terminal at the *left hand side*
- In this way we describe *global* data flow over a tree, by defining *local* data-flow building blocks, corresponding to the productions of the grammar

Introducing UUAG

- Special syntax for programming with attributes
- Domain specific language for specifying tree walks

This example:

- Attribute values do not influence the parsing process
- Semantic functions for the parser are generated from the attribute grammar

Creating HTML from a document

```
\section{Intro}
  \section{Section 1}
    \paragraph
      paragraph 1
    \end
    \paragraph
      paragraph 2
    \end
  \end
  \section{Section 2}
    \paragraph
      paragraph 1
    \end
    \paragraph
      paragraph 2
    \end
  \end \end
```

```
<h1>Intro</h1>
<h2>Section 1</h2>
<p>
  Paragraph 1
</p>
<p>
  Paragraph 2
</p>

<h2>Section 2</h2>
<p>
  Paragraph 1
</p>
<p>
  Paragraph 2
</p>
```

Concrete syntax

```
Docs  ::=  Doc*
Doc   ::=  \section { Text } Docs \end
         |  \paragraph Text \end
```

$$
\begin{aligned}
&pDocs :: Parser\ Token\ T\_Docs \\
&pDocs = pFoldr\_gr\ (sem\_Docs\_Cons, sem\_Docs\_Nil)\ pDoc \\
&pDoc :: Parser\ Token\ T\_Doc \\
&pDoc = \\
&\quad sem\_Doc\_Section\ \langle\$\ pKey\ \texttt{"\textbackslash Section"} \\
&\quad\ \langle*\rangle\ pPacked\ (pKey\ \texttt{"\{"})\ (pKey\ \texttt{"\}"})\ pText \\
&\quad\ \langle*\rangle\ pDocs\ \langle*\ pKey\ \texttt{"\textbackslash end"} \\
&\ \langle|\rangle \\
&\quad sem\_Doc\_Paragraph \\
&\quad\ \langle\$\ pKey\ \texttt{"\textbackslash Paragraph"}\ \langle*\rangle\ pText\ \langle*\ pKey\ \texttt{"\textbackslash end"}
\end{aligned}
$$

Abstract syntax

In our example we will use the Utrecht Attribute Grammar System, which borrows heavily from Haskell.

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- Grammars closely resemble Haskell data types:

$$\begin{array}{lll} \textbf{TYPE}\ \mathit{Docs} = [\mathit{Doc}] & & \\ \textbf{DATA}\ \mathit{Doc} & | \ \mathit{Section} & \mathit{title} : \mathit{String}\ \mathit{body} : \mathit{Docs} \\ & | \ \mathit{Paragraph} & \mathit{text} : \mathit{String} \end{array}$$

- $Docs$ and Doc are non-terminals
- $Section$ and $Paragraph$ label different productions
- $title$, $body$ and $string$ are names for children

Our First Attribute!

- We introduce an attribute $html$ of type $String$ to return the generated html code in a synthesized attribute:

$$\textbf{ATTR}\ Doc\ Docs\ [\quad |\quad |\quad html : String\quad]$$

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Our First Attribute!

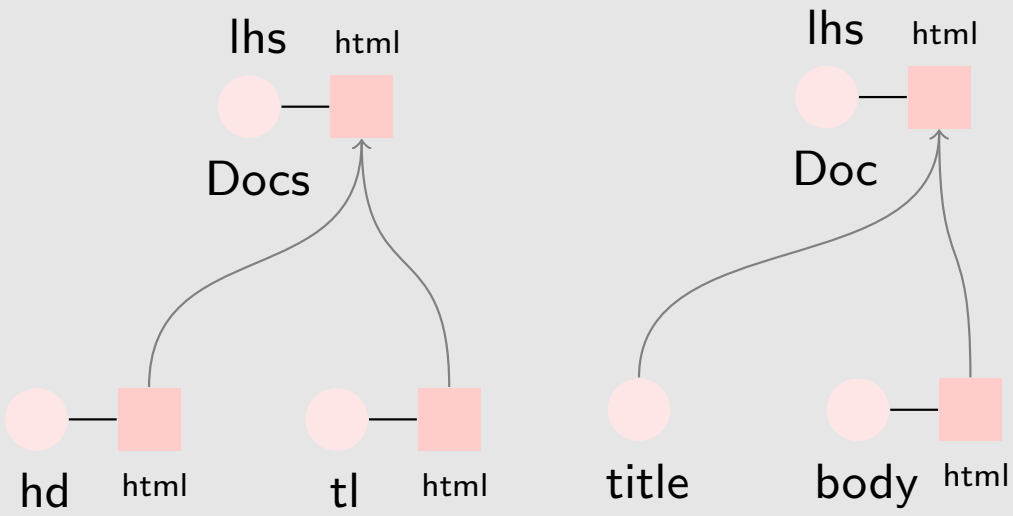
- We introduce an attribute *html* of type *String* to return the generated html code in a synthesized attribute:

$$\textbf{ATTR}\ \mathit{Doc}\ \mathit{Docs}\ [\quad |\quad |\quad \mathit{html} : \mathit{String}\quad]$$

- Definitions for attributes are given in Haskell, with embedded references to attributes, in the form of `@<ntname>.<attrname>`:

$$\begin{array}{ll}
\textbf{SEM}\ \mathit{Doc} & \\
\quad |\ \mathit{Section} & \textbf{lhs}.\mathit{html} = \texttt{"<bf>"} +\!\!+ @\mathit{title} +\!\!+ \texttt{"</bf>\textbackslash n"} \\
 & \qquad +\!\!+ @\mathit{body}.\mathit{html} \\
\quad |\ \mathit{Paragraph} & \textbf{lhs}.\mathit{html} = \texttt{"<P>"} +\!\!+ @\mathit{text} +\!\!+ \texttt{"</P>"} \\
\textbf{SEM}\ \mathit{Docs} & \\
\quad |\ \mathit{Cons} & \textbf{lhs}.\mathit{html} = @\mathit{hd}.\mathit{html} +\!\!+ @\mathit{tl}.\mathit{html} \\
\quad |\ \mathit{Nil} & \textbf{lhs}.\mathit{html} = \texttt{""}
\end{array}$$

A Picture



Adding The Level Aspect

- Introduce an **inherited** attribute with name $level$, indicating the nesting level of the headings:

$$\textbf{ATTR}\ Doc\ Docs\ [\quad level : Int \quad |\quad |\quad]$$

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- With the semantic rules:

$$\begin{aligned}&\textbf{SEM}\ Doc \mid Section\\ &\qquad body.level = @\textbf{lhs}.level + 1\\ &\qquad \textbf{lhs}.html \ := mk\_tag\ (\texttt{"H"} +\!\!+ show\ @\textbf{lhs}.level)\\ &\qquad\qquad\qquad\qquad\qquad \texttt{""}\ @title +\!\!+ @body.html\end{aligned}$$

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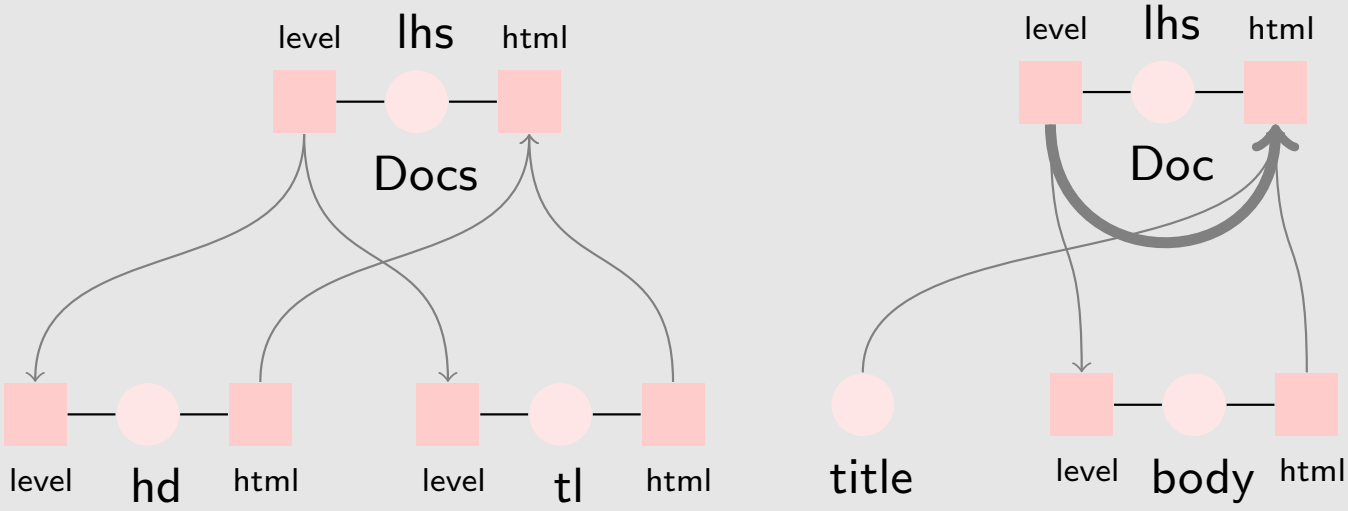
- Where the function mk_tag is defined by:

$$\begin{aligned}mk\_tag\ tag\ attrs\ elem = \quad &\texttt{"<"} +\!\!+ tag +\!\!+ attrs +\!\!+ \texttt{">"} +\!\!+ elem\\ &+\!\!+ \texttt{"</"} +\!\!+ tag +\!\!+ \texttt{">"}\end{aligned}$$

A Picture With level Added



Example

```
Section "Intro"
        [Section "Section 1"
                 [Paragraph "paragraph 1",
                 ,Paragraph "paragraph 2"
                 ]
        ,Section "Section 2"
                 [Paragraph "paragraph 3",
                 ,Paragraph "paragraph 4"
                 ]
        ]
```

Note The Following:

- We did not touch the original code
- We introduced a new inherited attribute with its definitions
- We only redefined the definition of $Doc.section.html$, hence the use of $:=$

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- We did not touch the original code
- We introduced a new inherited attribute with its definitions
- We only redefined the definition of $Doc.section.html$, hence the use of $:=$
- Maybe we also want to add yet another aspect: section counters

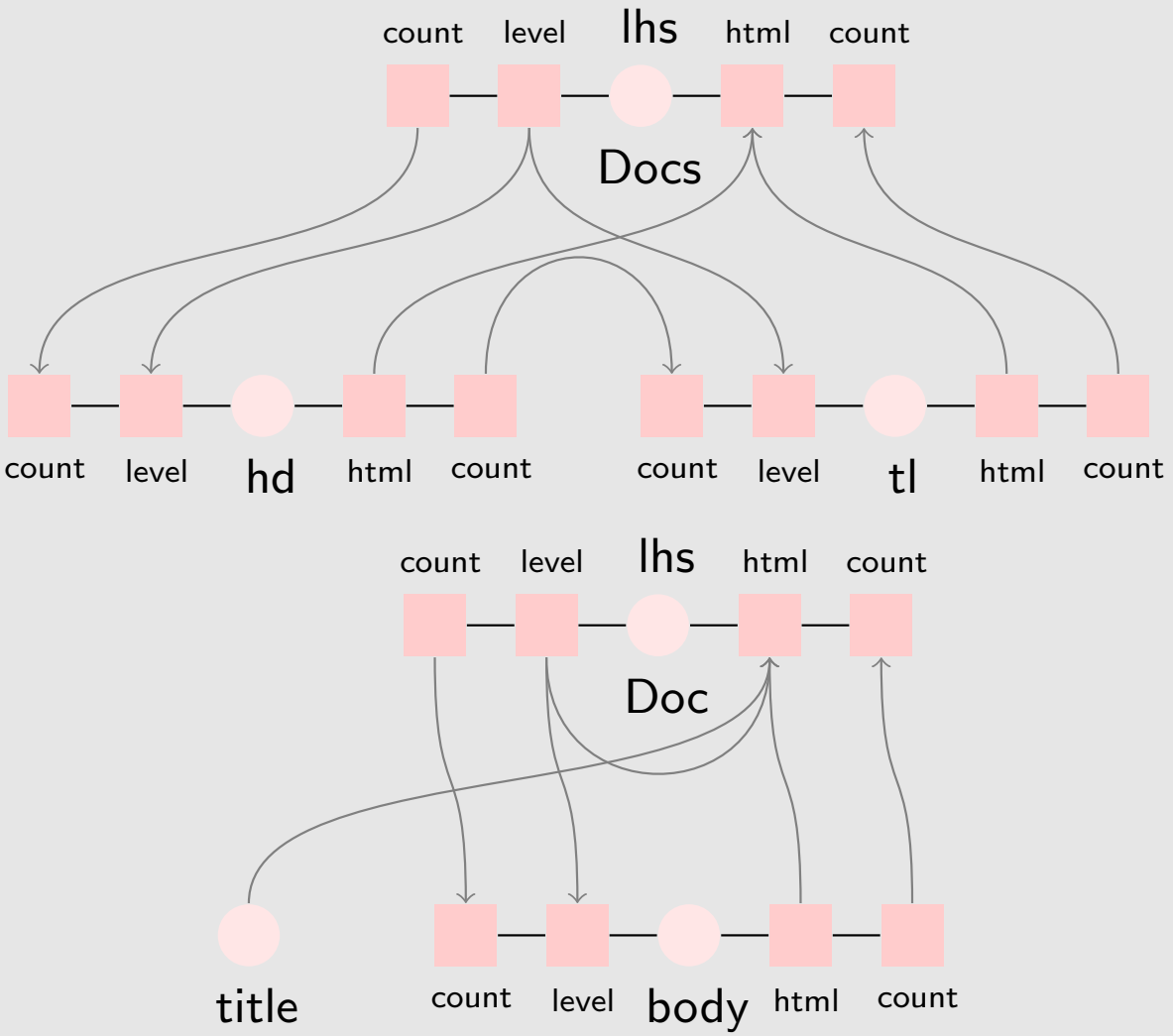
Adding The Section Counter Aspect

- Introduce two inherited attributes:
  - The $context$, representing the outer blocks
  - A $counter$ for keeping track of the number of encountered siblings.

$$\begin{array}{l}\textbf{ATTR}\ Doc\ Docs\ [\ \ context : String \\ \qquad\qquad\qquad\qquad\quad |\ \ count : Int \\ \qquad\qquad\qquad\qquad\quad |]\end{array}$$

- Since we do not now whether a Doc will update the counter we will have to pass it from $Docs$ to Doc, and back up again. So $count$ becomes a *threaded attribute*
- **loc** is a virtual non-terminal, with which we may associate local attributes

A picture With The count Added



The Semantic Functions

```
SEM Doc
  | Section body.count    = 1
            body.context  = @loc.prefix
            lhs.count     = @lhs.count + 1
            lhs.html      := @loc.html
            loc.prefix    = if      null @lhs.context
                            then  show @lhs.count
                            else  @lhs.context
                                  ++ "."
                                  ++ show @lhs.count
            loc.html      = mk_tag ("H" ++ show @lhs.level)
                                   ""
                                   (@loc.prefix ++ "  "
                                     ++ @title)
                            ++ @body.html
```

I expected more rules. What happened?

- We have not given rules for $count$ and $prefix$ for Docs?

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- We have not given rules for *count* and *prefix* for Docs?
- Since we generate copy rules in case attributes are passed on unmodified
- Some *copy rules* that were automatically generated are:

```
SEM Docs
  | Nil   lhs.count   = @lhs.count
  | Cons  hd.count    = @lhs.count
          tl.count    = @hd.count
          hd.context  = @lhs.context
          tl.context  = @lhs.context
          hd.level    = @lhs.level
          tl.level    = @lhs.level
```

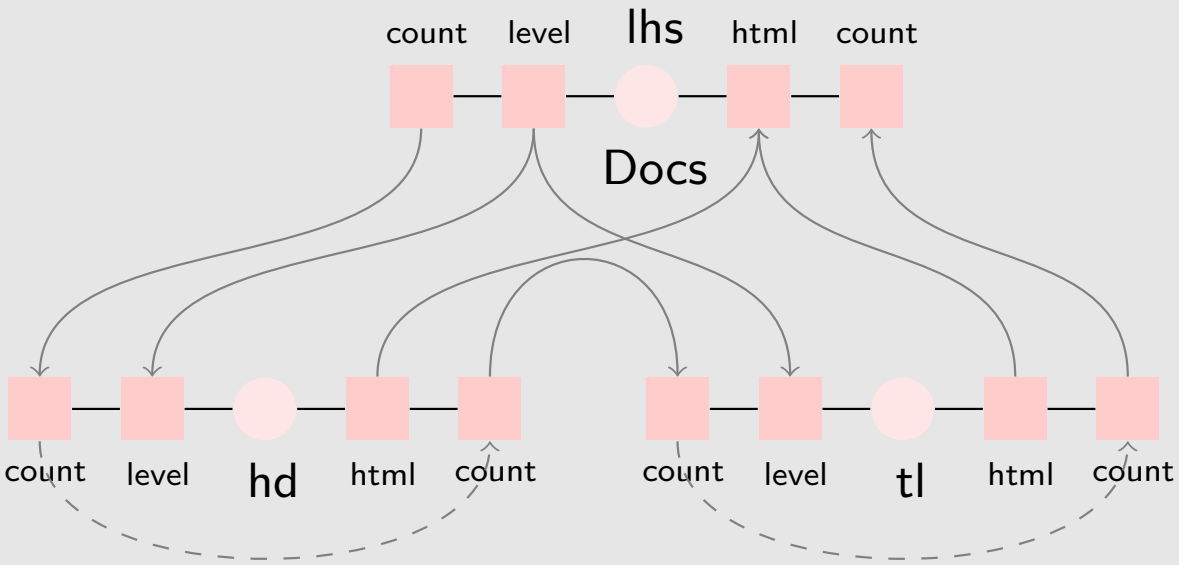
Copy rules

If a rule for an attribute $k.a$ is missing:

- Use $@\mathbf{loc}.a$
- Use $@c.a$ for the rightmost child c to the left of k, which has a synthesized attribute named a
- Use $@\mathbf{lhs}.a$

A Pictorial Representation

- We show some different aspects
- We show the aspects *count* and *level* and html



Adding Extra Productions

- We may also add extra productions, and as an example we will insert a table of contents

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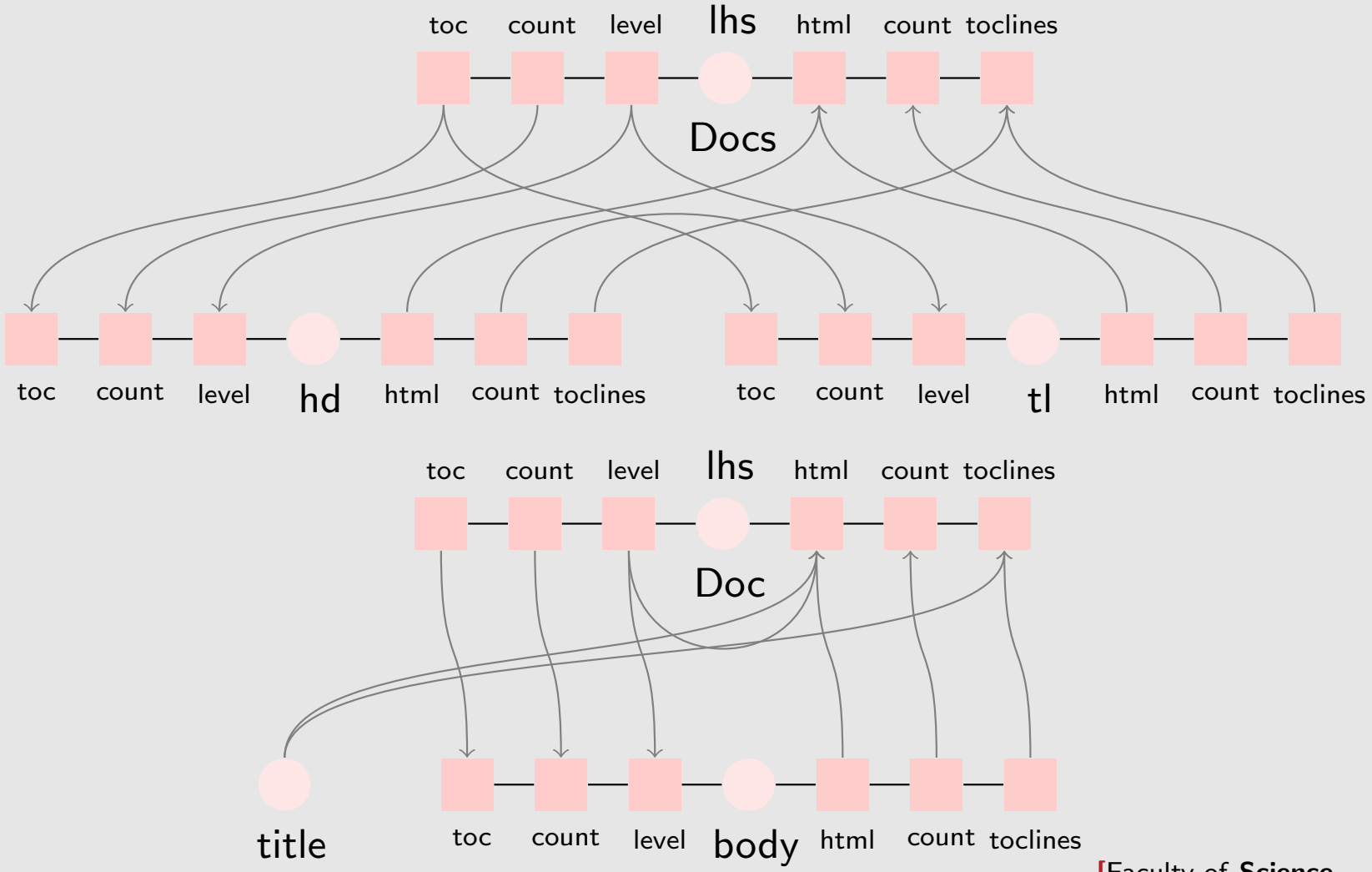
- We may also add extra productions, and as an example we will insert a table of contents
- An extra synthesized attribute $toclines$ in which the table of contents is constructed
- An extra inherited attribute toc, containing the table of contents

$$
\begin{array}{l}
\textbf{DATA}\ Root \quad | \ Root\ doc : Doc \\
\textbf{ATTR}\ Root\ [\,||\ html : String\,] \\
\textbf{DATA}\ Doc \quad | \ Toc \\
\textbf{ATTR}\ Doc\ Docs\ [\ toc : String \\
\qquad\qquad\qquad\qquad\ \ | \\
\qquad\qquad\qquad\qquad\ \ | \ toclines\ USE\{\#\}\{\texttt{""}\} : String\,]
\end{array}
$$

- The USE clause defines default semantic computation

A picture with the toc and toclines added



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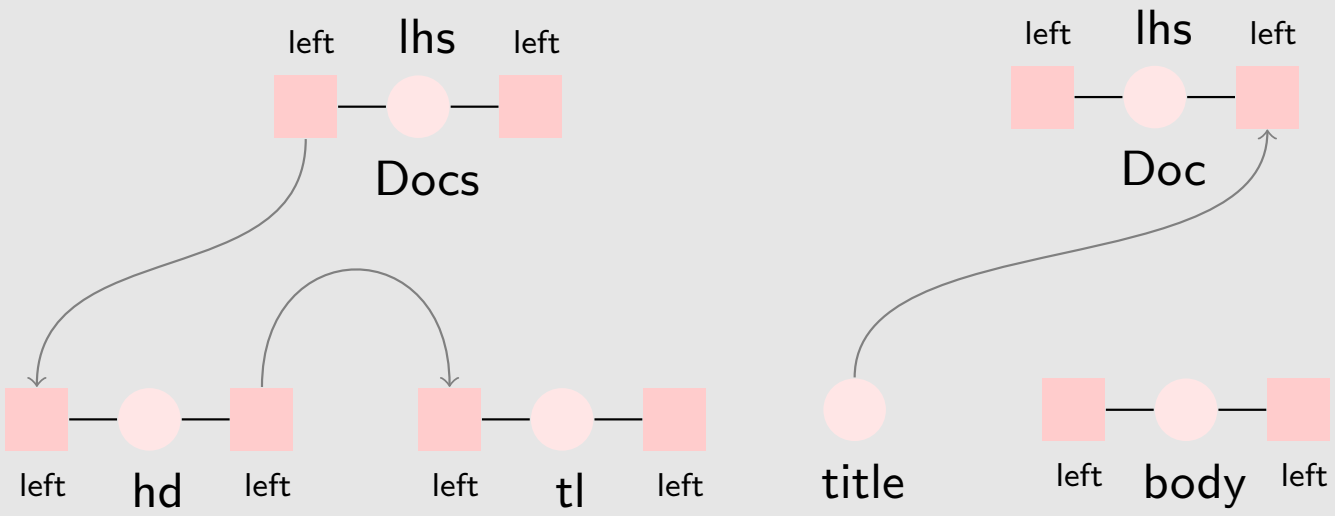
```
SEM Doc
  | Section
      lhs .toclines = mk_tag "LI" ""
                      (mk_tag ("A")
                      (" HREF=#" ++ @loc.prefix)
                      (@loc.prefix ++ "  "
                       ++ @title))
                       ++ mk_tag "UL" ""@body.toclines
      lhs .html     := mk_tag "A" (" NAME="
                       ++ @loc.prefix) ""
                       ++ @loc.html
  | Toc lhs .html    = @lhs.toc
SEM Root
  | Root doc.toc     = @doc.toclines
         doc.level   = 1
         doc.context = ""
         doc.count   = 1
```

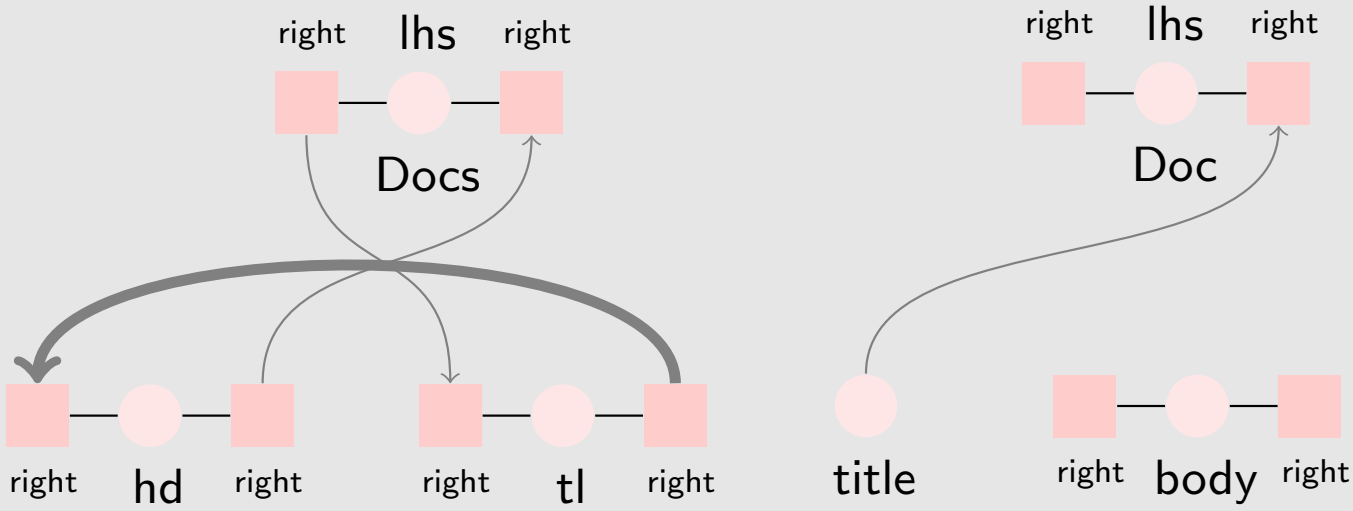
Backward Flow Of Data

- We want to be able to jump to the section to the $left$ and the $right$ of the current section
- We introduce two new attributes for passing this information around

Left


left
lhs
left
Docs
left
hd
left
left
tl
left
left
lhs
left
Doc
title
left
body
left

Right



SEM *Docs*
| *Cons*
$hd.right = @tl.right$
$tl.right = @\mathbf{lhs}.right$
$\mathbf{lhs}.right = @hd.right$

SEM *Doc*
| *Section*
$\mathbf{lhs}.right = @title$
$body.right =$ ""

Current Situation

- Attribute grammars are a domain specific language for describing *catamorphisms*

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- Attribute grammars are a domain specific language for describing *catamorphisms*
- With higher-order domains, i.e. we assign functions mapping *inherited* to *synthesized attributes*
- Different systems differ in what kind of specific patterns of attribution being supported, such as:
  - The copy rules we have seen
  - The USE clause that was used to cmbine attribute values presented by children
  - Some systems allow to refer to *far away* attributes

What Is Generated?

- Data types

$$
\begin{aligned}
\textbf{data}\ Doc = {} & Doc\_Paragraph\ String \\
\mid {} & Doc\_Section\ String\ Docs \\
\mid {} & Doc\_Toc
\end{aligned}
$$

What Is Generated?

- Data types

$$\begin{aligned}\textbf{data}\ Doc = {} & Doc\_Paragraph\ String \\ \mid {} & Doc\_Section\ String\ Docs \\ \mid {} & Doc\_Toc\end{aligned}$$

- Types

$$\begin{aligned}\textbf{type}\ T\_Doc = {} & String \rightarrow \\ & Int \rightarrow \\ & Int \rightarrow \\ & String \rightarrow \\ & (Int, String, String)\end{aligned}$$

... And ...

Semantic functions:

```
sem_Docs_Cons (_hd) (_tl) =
  λ_lhs_context
    _lhs_count
    _lhs_level
    _lhs_toc →
      let (_hd_count, _hd_html, _hd_toclines) =
      (_hd (_lhs_context) (_lhs_count) (_lhs_level) (_lhs_toc))
          (_tl_count, _tl_html, _tl_toclines) =
      (_tl (_lhs_context) (_hd_count) (_lhs_level) (_lhs_toc))
      in  (_tl_count, _hd_html ++ _tl_html
          , _ hd_toclines ++ _tl_toclines)
```

Optimizations

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- Perform an abstract interpretation of the grammar
- Computing dependencies between attributes
- Schedule the attributes for computation per non-terminal (multiple visits)
- And is this way achieve a data-driven evaluation
- That may be somewhat cheaper
- And takes far less space

What is generated now?

Type signatures:

$$
\begin{aligned}
&\textbf{type } T\_Doc = Int \rightarrow \\
&\quad String \rightarrow \\
&\quad ([Int]) \rightarrow \\
&\quad (Int, PP\_Doc, String, T\_Doc\_1) \\
&\textbf{type } T\_Doc\_1 = Int \rightarrow \\
&\quad String \rightarrow \\
&\quad PP\_Doc \rightarrow \\
&\quad (PP\_Doc, String)
\end{aligned}
$$

... And ...

Semantic functions:

```
sem_Docs_Cons :: T_Doc → T_Docs → T_Docs
sem_Docs_Cons !hd_ !tl_ =
  (λ(!_lhsIcount) (!_lhsIleft) (!_lhsIprefix) →
    (case (_lhsIprefix) of
      {!_tlOprefix →
       ...
         (case ((hd_ _hdOcount _hdOleft _hdOprefix)) of
           {(!_hdIcount, !_hdIgathToc, !_hdIleft, !hd_1) →
            ...
              (case ((tl_ _tlOcount _tlOleft _tlOprefix)) of
                {(!_tlIgathToc, !tl_1) →
                 ...
                   {(!sem_Docs_1) →
                   (_lhsOgathToc, sem_Docs_1)})
```

... And ...

Semantic functions:

```
sem_Docs_Cons_1 :: String → T_Docs_1 →
   T_Doc_1 → T_Docs_1
sem_Docs_Cons_1 ! _hdIleft ! tl_1 ! hd_1 =
   (λ(!_lhsIlevel) (!_lhsIright) (!_lhsItoc) →
      (case (_lhsItoc) of
         {!_tlOtoc →
         (case (_lhsIlevel) of
          ...
            (case ((tl_1 _tlOlevel _tlOright _tlOtoc)) of
               {(!_tlIcount, !_tlIhtml, !_tlIleft, !_tlIright) →
               (case (_tlIcount) of
                ...
                  (case (_hdIhtml >-< _tlIhtml) of
                   ...
                     (_lhsOcount, _lhsOhtml, _lhsOleft, _lhsOright)})
```

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- We use Haskell as the target language
- And Haskell has lazy/demand driven evaluation
- And so we do not have to schedule the computations ourselves
- Furthermore we borrow:
  - The type system from Haskell
  - The language for defining the semantic functions

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If we look at object oriented languages we see that:

- It is easy to define a subclass: simply provide a method contributing its part for each property we are interested in.

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If we look at object oriented languages we see that:

- It is easy to define a subclass: simply provide a method contributing its part for each property we are interested in.
- It is difficult to add a property to a data type, since we have to update all subclasses with a new method

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- You may "grow" a system by:

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- Attribute grammars do not force you to think along either axis
- You may "grow" a system by:
  - Stepwise adding extra productions to data types
  - Stepwise adding extra attributes
- Aspects are largely independent
- But interactions can take place by just referring to other aspects
- The system will weave things together

Conclusions

- Attribute grammars are your friend if you want to implement a language
- Attributes may even depend on themselves if you are building on a lazy language
- Even thinking in terms of attribute grammars you my construct interesting programs

- `http://www.cs.uu.nl/wiki/HUT/WebHome`
- or check your CD