4. Attribute grammars and semantic analysis

Input: **abstract program tree**

Tasks:	**Compiler module:**
name analysis	environment module
properties of program entities	definition module
type analysis, operator identification	signature module

Output: **attributed program tree**

Standard implementations and generators for compiler modules

Operations of the compiler modules are called at nodes of the abstract program tree

Model: dependent computations in trees

Specification: **attribute grammars**

generated: a **tree walking algorithm** that calls functions of semantic modules **in specified contexts** and in an **admissible order**

Objectives:

Tasks and methods of semantic analysis

In the lecture:

Explanation of the

- tasks,
- compiler modules,
- principle of dependent computations in trees.

Suggested reading:

Kastens / Übersetzerbau, Section Introduction of Ch. 5 and 6

4.1 Attribute grammars

Attribute grammar (AG): specifies **dependent computations in abstract program trees; declarative**: explicitly specified dependences only; a suitable order of execution is computed

Computations solve the tasks of semantic analysis (and transformation)

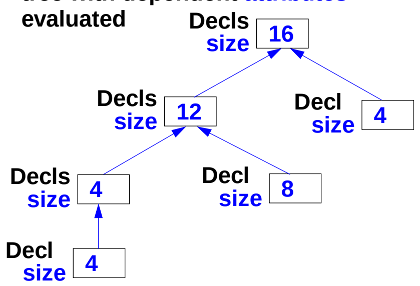
Generator produces **a plan for tree walks**
that execute calls of the computations,
such that the specified dependences are obeyed,
computed values are propagated through the tree

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

Example: AG specifies size of declarations

```
RULE: Decls ::= Decls Decl COMPUTE
    Decls[1].size =
        Add (Decls[2].size, Decl.size);
END;
RULE: Decls ::= Decl COMPUTE
    Decls.size = Decl.size;
END;
RULE: Decl ::= Type Name COMPUTE
    Decl.size = Type.size;
END;
```

tree with dependent attributes evaluated



Objectives:

Get an informal idea of attribute grammars

In the lecture:

Explain computations in tree contexts using the example

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

Questions:

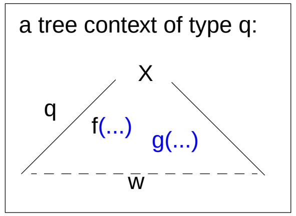
Why is it useful NOT to specify an evaluation order explicitly?

Basic concepts of attribute grammars (1)

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

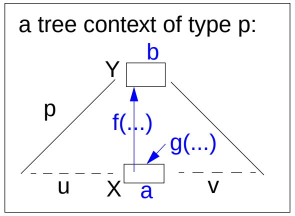
```
RULE q: X ::= w COMPUTE
   f(...); g(...);
END;
```

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



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

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



Attributes represent: **properties of symbols** and
pre- and post-conditions of computations:
post-condition = f (pre-condition)
f(X.a) uses the result of g(...); hence
X.a = g(...) is specified to be executed before f(X.a)

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Objectives:

Get a basic understanding of AGs

In the lecture:

Explain

- the AG notation,
- dependent computations

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

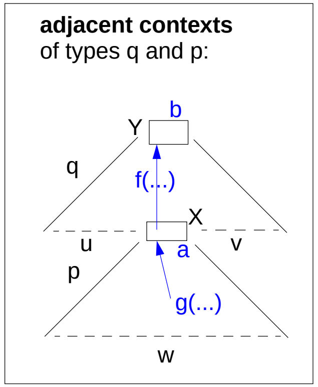
Assignments:

- Read and modify examples in Lido notation to introduce AGs

Basic concepts of attribute grammars (2)

dependent computations in adjacent contexts:

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



attributes may specify
dependences without propagating any value;
specifies the order of effects of computations:

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

`ResetTypeOf` will be called before `GetTypeOf`

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Objectives:

Get a basic understanding of AGs

In the lecture:

Explain

- dependent computations in adjacent contexts in trees

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

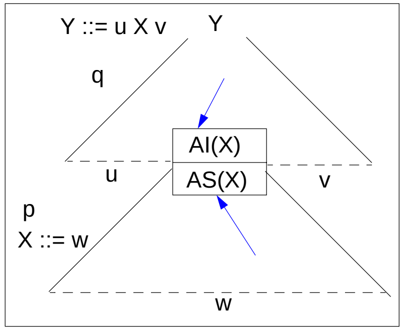
Assignments:

- Read and modify examples in Lido notation to introduce AGs

Definition of attribute grammars

An **attribute grammar** AG = (G, A, C) is defined by

- a **context-free grammar G** (abstract syntax)
- for each **symbol X** of G a set of **attributes A(X)**, written X.a if a ∈ A(X)
- for each **production (rule) p** of G a set of **computations** of one of the forms
  X.a = f (... Y.b ...)   or   g (... Y.b ...)
  where X and Y occur in p



Consistency and completeness of an AG:

Each A(X) is partitioned into two disjoint subsets: AI(X) and AS(X)

AI(X): **inherited attributes** are computed in rules p where X is on the **right**-hand side of p

AS(X): **synthesized attributes** are computed in rules p where X is on the **left**-hand side of p

Each rule p: Y::= ... X... has exactly one computation
for each attribute of AS(Y), for the symbol on the left-hand side of p, and
for each attribute of AI(X), for each symbol occurrence on the right-hand side of p

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Objectives:

Formal view on AGs

In the lecture:

The completeness and consistency rules are explained using the example of PLaC-4.6

AG Example: Compute expression values

The AG specifies: The value of each expression is computed and printed at the root:

```
ATTR value: int;

RULE: Root ::=  Expr  COMPUTE
  printf ("value is %d\n",
          Expr.value);
END;

TERM Number: int;

RULE: Expr ::= Number COMPUTE
  Expr.value = Number;
END;

RULE: Expr ::= Expr Opr Expr
COMPUTE
  Expr[1].value = Opr.value;
  Opr.left  = Expr[2].value;
  Opr.right = Expr[3].value;
END;
```

```
SYMBOL Opr: left, right: int;

RULE: Opr ::=  '+'  COMPUTE
  Opr.value  =
     ADD (Opr.left, Opr.right);
END;

RULE: Opr ::=  '*'  COMPUTE
  Opr.value =
     MUL (Opr.left, Opr.right);
END;
```

A (Expr) = AS(Expr) = {value}

AS(Opr) = {value}
AI(Opr) = {left, right}

A(Opr) = {value, left, right}

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Objectives:

Exercise formal definition

In the lecture:

- Show synthesized, inherited attributes.
- Check consistency and completeness.

Questions:

- Add a computation such that a pair of sets AI(X), AS(X) is no longer disjoint.
- Add a computation such that the AG is inconsistent.
- Which computations can be omitted whithout making the AG incomplete?
- What would the effect be if the order of the three computations on the bottom left of the slide was altered?

AG Binary numbers

Attributes:

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

```
RULE p1:   D ::= L '.' L   COMPUTE
   D.v = ADD (L[1].v, L[2].v);
   L[1].s = 0;
   L[2].s = NEG (L[2].lg);
END;
RULE p2:   L ::= L B       COMPUTE
   L[1].v = ADD (L[2].v, B.v);
   B.s = L[1].s;
   L[2].s = ADD (L[1].s, 1);
   L[1].lg = ADD (L[2].lg, 1);
END;
RULE p3:   L ::= B         COMPUTE
   L.v = B.v;
   B.s = L.s;
   L.lg = 1;
END;
RULE p4:   B ::= '0'       COMPUTE
   B.v = 0;
END;
RULE p5:   B ::= '1'       COMPUTE
   B.v = Power2 (B.s);
END;
```

scaled binary value:

$B.v = 1 * 2^{B.s}$

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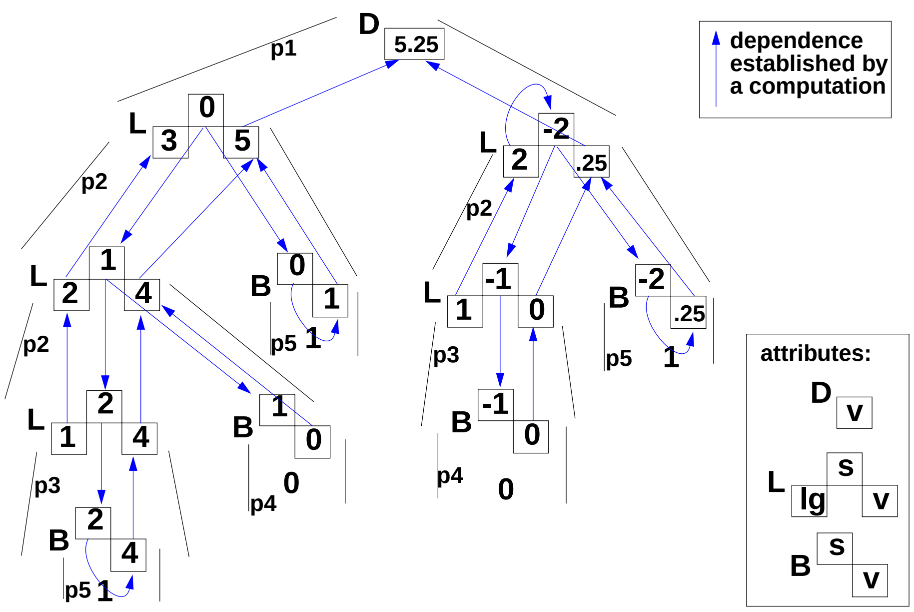
Objectives:

A complete example for an AG

In the lecture:

- Explain the task.
- Explain the role of the attributes.
- Explain the computations in tree contexts.
- Show a tree with attributes and dependencies (PLaC-4.8)

An attributed tree for AG Binary numbers



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Objectives:

An attributed tree

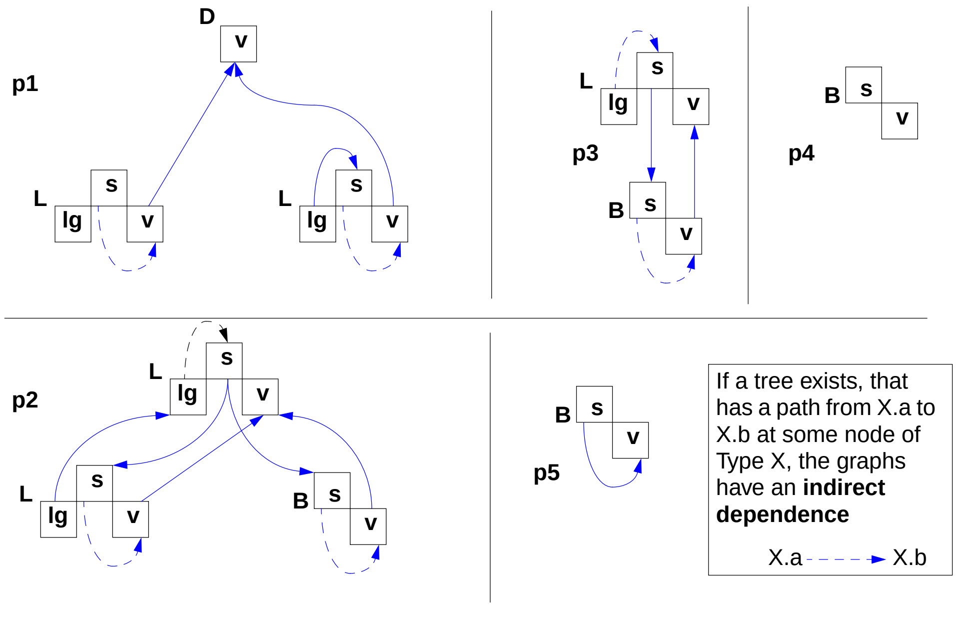
In the lecture:

- Show a tree with attributes.
- Show tree contexts specified by grammar rules.
- Relate the dependences to computations.
- Evaluate the attributes.

Questions:

- Some attributes do not have an incoming arc. Why?
- Show that the attribues of each L node can be evaluated in the order lg, s, v.

Dependence graphs for AG Binary numbers



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Objectives:

Represent dependences

In the lecture:

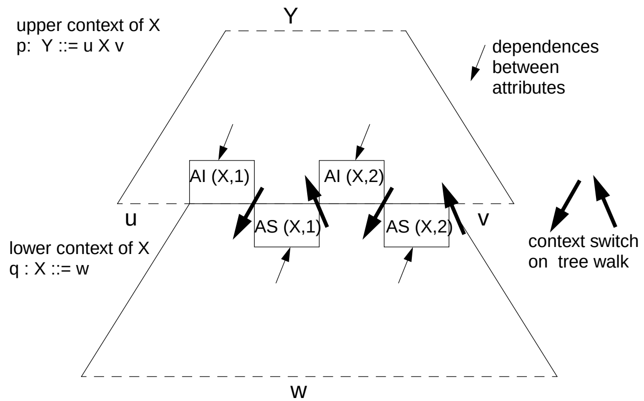
- graph representation of dependences that are specified by computations,
- compose the graphs to yield a tree with dependences,
- explain indirect dependences
- Use the graphs as an example for partitions (PLaC-4.9)
- Use the graphs as an example for LAG(k) algorithm (see a later slide)

Attribute partitions

The sets AI(X) and AS(X) are **partitioned** each such that

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

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



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

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Objectives:

Understand the concept of attribute partitions

In the lecture:

Explain the concepts

- context switch,
- attribute partitions: sequence of disjoint sets which alternate between synthesized and inherited

Suggested reading:

Kastens / Übersetzerbau, Section 5.2

Assignments:

Construct AGs that are as simple as possible and each exhibits one of the following properties:

- There are some trees that have a dependence cycle, other trees don't.
- The cycles extend over more than one context.
- There is an X that has a partition with k=2 but not with k=1.
- There is no partition, although no tree exists that has a cycle. (caution: difficult puzzle!)

(Exercise 22)

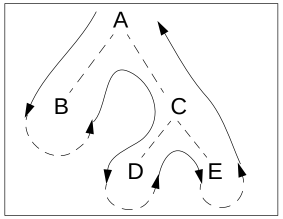
Construction of attribute evaluators

For a given attribute grammar an attribute evaluator is constructed:

- It is **applicable to any tree** that obeys the abstract syntax specified in the rules of the AG.
- It performs a **tree walk** and **executes computations** in visited contexts.
- The execution order obeys the **attribute dependences**.

Pass-oriented strategies for the tree walk: **AG class:**

k times **depth-first left-to-right**	**LAG (k)**
k times depth-first right-to-left	RAG (k)
alternatingly left-to-right / right-to left	**AAG (k)**
once **bottom-up (synth. attributes only)**	**SAG**

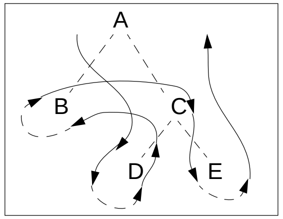


AG is checked if attribute dependences
fit to desired pass-oriented strategy; see LAG(k) check.

non-pass-oriented strategies:

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

A generator fits the plans to the dependences of the AG.



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Objectives:

Tree walk strategies

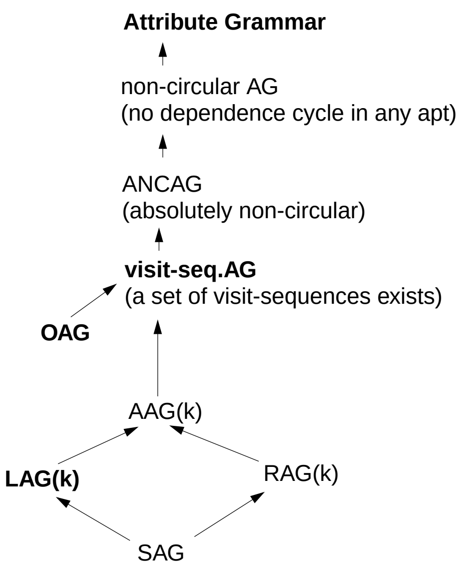
In the lecture:

- Show the relation between tree walk strategies and attribute dependences.

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

Hierarchy of AG classes



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Objectives:

Understand the AG hierarchy

In the lecture:

It is explained

- A grammar class is more powerful if it covers AGs with more complex dependencies.
- The relationship of AG classes in the hierarchy.

Suggested reading:

Kastens / Übersetzerbau, Section 5, 5.1

Visit-sequences

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

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

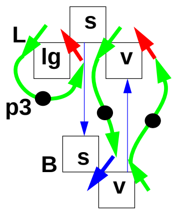
A visit-sequence is a **sequence of operations**:

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

Example out of the AG for binary numbers:

vs_{p3}: L ::= B

L.lg=1; ↑1; B.s=L.s; ↓B,1; L.v=B.v; ↑2



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Objectives:

Understand the concept of visit-sequences

In the lecture:

Using the example it is explained:

- operations,
- context switch,
- sequence with respect to a context

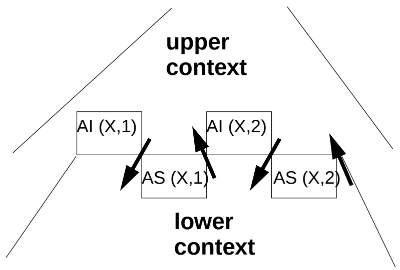
Suggested reading:

Kastens / Übersetzerbau, Section 5.2.2

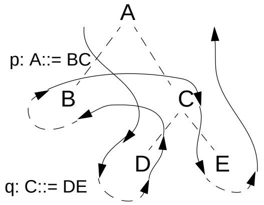
Interleaving of visit-sequences

Visit-sequences for adjacent contexts are executed interleaved.

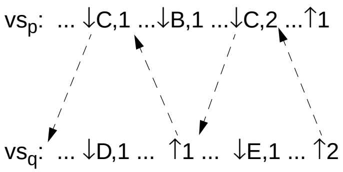
The **attribute partition** of the common nonterminal specifies the **interface** between the upper and lower visit-sequence:



Example in the tree:



interleaved visit-sequences:



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

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Objectives:

Understand interleaved visit-sequences

In the lecture:

Explain

- interleaving of visit-sequences for adjacent contexts,
- partitions are "interfaces" for context switches,
- implementation using procedures and calls

Suggested reading:

Kastens / Übersetzerbau, Section 5.2.2

Assignments:

- Construct a set of visit-sequences for a small tree grammar, such that the tree walk solves a certain task.
- Find the description of the design pattern "Visitor" and relate it to visit-sequences.

Questions:

- Describe visit-sequences which let trees being traversed twice depth-first left-to-right.

Visit-sequences for the AG Binary numbers

vs_{p1}: D ::= L '.' L

↓L[1],1; L[1].s=0; ↓L[1],2; ↓L[2],1; L[2].s=NEG(L[2].lg);

↓L[2],2; D.v=ADD(L[1].v, L[2].v); ↑1

vs_{p2}: L ::= L B

↓L[2],1; L[1].lg=ADD(L[2].lg,1); ↑1

L[2].s=ADD(L[1].s,1); ↓L[2],2; B.s=L[1].s; ↓B,1; L[1].v=ADD(L[2].v, B.v); ↑2

vs_{p3}: L ::= B

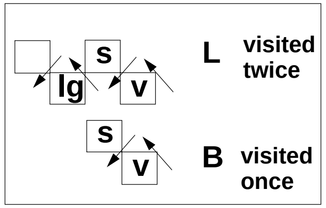
L.lg=1; ↑1; B.s=L.s; ↓B,1; L.v=B.v; ↑2

vs_{p4}: B ::= '0'

B.v=0; ↑1

vs_{p5}: B ::= '1'

B.v=Power2(B.s); ↑1



Implementation:

Procedure vs<i><p> for each section of a vs_p to a ↑i

a call with a switch over alternative rules for ↓X,i

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Objectives:

Example for visit-sequences used in PLaC-4.13

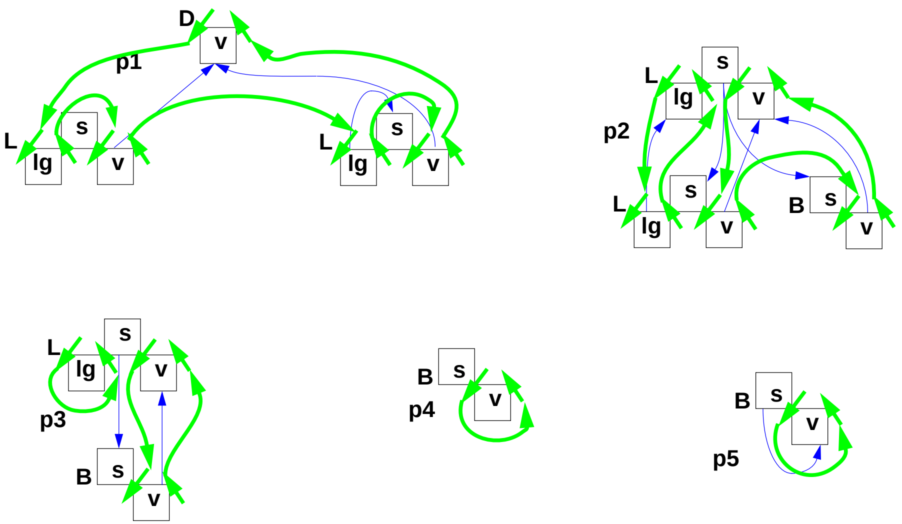
In the lecture:

- Show interfaces and interleaving,
- show tree walk (PLaC-4.15),
- show sections for implementation.

Questions:

- Check that adjacent visit-sequences interleave correctly.
- Check that all dependencies between computations are obeyed.
- Write procedures that implement these visit-sequences.

Visit-Sequences for AG Binary numbers (tree patterns)



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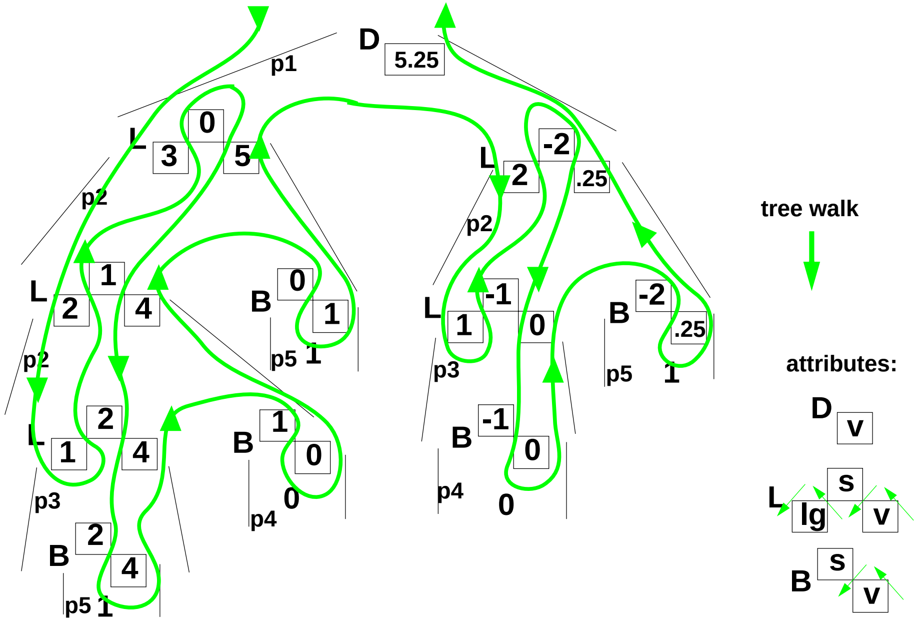
Objectives:

Example for visit-sequences used in PLaC-4.13

In the lecture:

- Create a tree walk by pasting instances of visit-sequnces together

Tree walk for AG Binary numbers



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Objectives:

See a concrete tree walk

In the lecture:

Show that the visit-sequences of PLaC-4.15 produce this tree walk for the tree of PLaC-4.8.

LAG (k) condition

An AG is a LAG(k), if:

For each symbol X there is an **attribute partition** A (X,1), ..., A (X, k),
such that the attributes in **A (X, i) can be computed in the i-th depth-first left-to-right pass**.

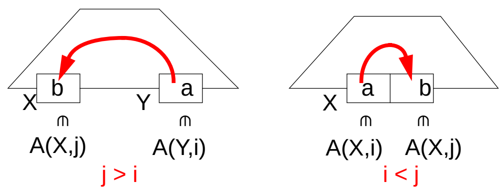
Crucial dependences:

In every dependence graph every dependence

- **Y.a -> X.b** where X and Y occur on the **right-hand side** and **Y is right of X** implies that **Y.a belongs to an earlier pass than X.b**, and
- **X.a -> X.b** where X occurs on the **right-hand side** implies that **X.a belongs to an earlier pass than X.b**

Necessary and sufficient condition over dependence graphs - expressed graphically:

A dependency
from right to left



A dependence
at one symbol
on the right-hand side

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Objectives:

Understand the LAG condition

In the lecture:

- Explain the LAG(k) condition,
- motivate it by depth-first left-to-right tree walks.

Suggested reading:

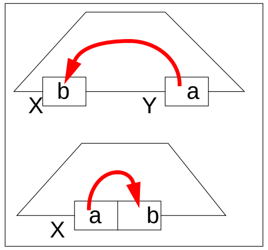
Kastens / Übersetzerbau, Section 5.2.3

LAG (k) algorithm

Algorithm checks whether there is a **k>=1** such that an **AG is LAG(k)**.

Method:
compute iteratively **A(1)**, ..., **A(k)**;
in each iteration try to allocate all remaining attributes to the current pass, i.e. **A(i)**;
remove those which can not be evaluated in that pass

Algorithm:



Set **i=1** and **Cand=** all attributes

repeat
set **A(i) = Cand**; set **Cand** to empty;

while still attributes can be removed from **A(i)** do
remove an attribute X.b from A(i) and add it to **Cand** if
- there is a **crucial dependence**
Y.a -> X.b s.t.
X and **Y** are on the right-hand side, **Y** to the right of **X** and **Y.a** in **A(i)** or
X.a -> X.b s.t. **X** is on the right-hand side and **X.a** is in **A(i)**
- **X.b** depends on an attribute that is not yet in any **A(i)**

if **Cand** is empty: exit: the AG **is LAG(k)** and all attributes are assigned to their passes
if **A(i)** is empty: exit: the AG **is not LAG(k) for any k**
else: set i = i + 1

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Objectives:
Understand the LAG(k) check

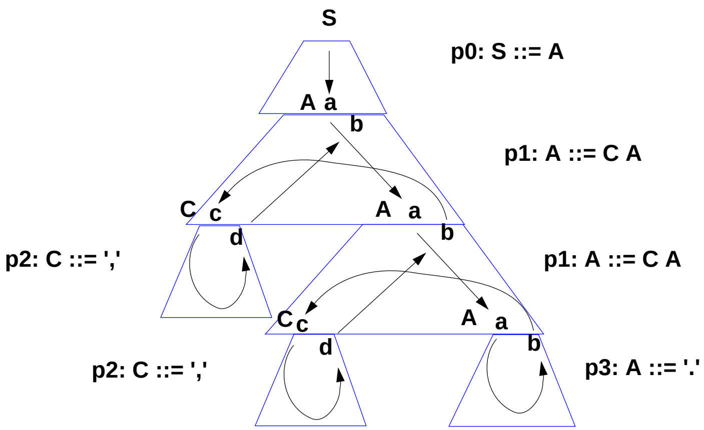
In the lecture:
- explain the algorithm using the example of PLaC-4.10.

Suggested reading:
Kastens / Übersetzerbau, Section 5.2.3

Assignments:
- Check LAG(k) condition for AGs (Exercise 20)

Questions:
- At the end of each iteration of the i-loop one of three conditions hold. Explain them.

AG not LAG(k) for any k



A.a can be allocated to the first left-to-right pass.
C.c, C.d, A.b can not be allocated to any pass.

The AG is RAG(1), AAG(2) and
can be evaluated by visit-sequences.

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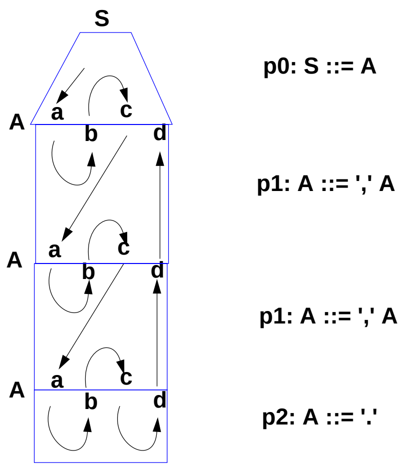
Objectives:
Understand a non-LAG pattern

In the lecture:
- Explain the tree,
- derive the AG,
- try the LAG(k) algorithm.

AG not evaluable in passes

No attribute can be allocated to any pass for any strategy.

The AG can be evaluated by visit-sequences.



Objectives:

Understand a non-pass pattern

In the lecture:

- Explain the tree,
- derive the AG,
- try the LAG(k) algorithm.

Generators for attribute grammars

LIGA	University of Paderborn	OAG
FNC-2	INRIA	ANCAG (superset of OAG)
CoCo	Universität Linz	LAG(k)

Properties of the generator LIGA

- integrated **in the Eli system**, cooperates with other Eli tools
- **high level specification language** Lido
- modular and **reusable AG components**
- object-oriented constructs usable for **abstraction of computational patterns**
- computations are **calls of functions** implemented outside the AG
- **side-effect computations** can be controlled by dependencies
- notations for **remote attribute access**
- **visit-sequence** controlled attribute evaluators, implemented in C
- **attribute storage optimization**

Objectives:

See what generators can do

In the lecture:

- Explain the generators
- Explain properties of LIGA

Suggested reading:

Kastens / Übersetzerbau, Section 5.4

Explicit left-to-right depth-first propagation

```
ATTR pre, post: int;
RULE: Root ::= Block COMPUTE
  Block.pre = 0;
END;
RULE: Block ::= '{' Constructs '}' COMPUTE
  Constructs.pre = Block.pre;
  Block.post = Constructs.post;
END;
RULE: Constructs ::= Constructs Construct COMPUTE
  Constructs[2].pre = Constructs[1].pre;
  Construct.pre = Constructs[2].post;
  Constructs[1].post = Construct.post;
END;
RULE: Constructs ::= COMPUTE
  Constructs.post = Constructs.pre;
END;
RULE: Construct ::= Definition COMPUTE
  Definition.pre = Construct.pre;
  Construct.post = Definition.post;
END;
RULE: Construct ::= Statement COMPUTE
  Statement.pre = Construct.pre;
  Construct.post = Statement.post;
END;
RULE:Definition ::= 'define' Ident ';' COMPUTE
  Definition.printed =
     printf ("Def %d defines %s in line %d\n",
             Definition.pre, StringTable (Ident), LINE);
  Definition.post =
     ADD (Definition.pre, 1) <- Definition.printed;
END;
RULE: Statement ::= 'use' Ident ';' COMPUTE
  Statement.post = Statement.pre;
END;
RULE: Statement ::= Block COMPUTE
  Block.pre = Statement.pre;
  Statement.post = Block.post;
END;
```

Definitions are enumerated and printed from left to right.

The next **Definition** number is propagated by a pair of attributes at each node:

pre (inherited)
post (synthesized)

The value is initialized in the **Root** context and

incremented in the **Definition** context.

The computations for propagation are systematic and redundant.

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Objectives:

Understand left-to-right propagation

In the lecture:

Explain

- systematic use of attribute pairs for propagation,
- strict dependences of computations on the "propagation chain".

Questions:

How would the output look like if we had omitted the state attributes and their dependencies?

Left-to-right depth-first propagation using a CHAIN

```
CHAIN count: int;

RULE: Root ::= Block COMPUTE
   CHAINSTART Block.count = 0;
END;

RULE: Definition ::= 'define' Ident ';'
COMPUTE
   Definition.print =
      printf ("Def %d defines %s in line %d\n",
              Definition.count, /* incoming */
              StringTable (Ident), LINE);

   Definition.count = /* outgoing */
      ADD (Definition.count, 1)
      <- Definition.print;
END;
```

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

One CHAIN name; attribute pairs are generated where needed.

CHAINSTART initializes the CHAIN in the root context of the CHAIN.

Computations on the CHAIN are **strictly bound** by dependences.

Trivial computations of the form X.pre = Y.pre in CHAIN order can be **omitted**. They are generated where needed.

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Objectives:

Understand LIDO's CHAIN constructs

In the lecture:

- Explain the CHAIN constructs.
- Compare the example with PLaC-4.19.

Dependency pattern INCLUDING

```
ATTR depth: int;
RULE: Root ::= Block COMPUTE
  Block.depth = 0;
END;
RULE: Statement ::= Block COMPUTE
  Block.depth =
     ADD (INCLUDING Block.depth, 1);
END;
RULE: Definition ::= 'define' Ident  COMPUTE
  printf ("%s defined on depth %d\n",
           StringTable (Ident),
           INCLUDING Block.depth);
END;
```

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

The nesting depths of **Blocks** are computed.

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

Propagation from computation to the uses are generated as needed.

No explicit computations or attributes are needed for the remaining rules and symbols.

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Objectives:

Understand the LIDO construct INCLUDING

In the lecture:

Explain the use of the INCLUDING construct.

Dependency pattern CONSTITUENTS

```
RULE: Root ::= Block COMPUTE
   Root.DefDone =
      CONSTITUENTS Definition.DefDone;
END;

RULE: Definition ::= 'define' Ident ';'
COMPUTE
   Definition.DefDone =
      printf ("%s defined in line %d\n",
              StringTable (Ident), LINE);
END;

RULE: Statement ::= 'use' Ident ';' COMPUTE
   printf ("%s used in line %d\n",
           StringTable (Ident), LINE)
   <- INCLUDING Root.DefDone;
END;
```

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

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

Propagation from computation to the **CONSTITUENTS** construct is generated where needed.

The shown combination with **INCLUDING** is a common dependency pattern.

All **printf** calls in **Definition** contexts are done before any in a **Statement** context.

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Objectives:

Understand the LIDO construct CONSTITUENTS

In the lecture:

Explain the use of the CONSTITUENTS construct.