Lecture 07 – attribute grammars + intro to IR

THEORY OF COMPILATION

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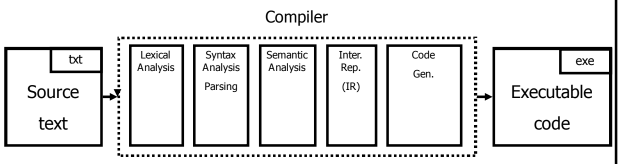


Last Week: Types

- What is a type?
  - Simplest answer: a set of values
  - Integers, real numbers, booleans, …
- Why do we care?
  - Safety
    - Guarantee that certain errors cannot occur at runtime
  - Abstraction
    - Hide implementation details
  - Documentation
  - Optimization

Last Week: Type System

- A type system of a programming language is a way to define how “good” program behave
  - Good programs = well-typed programs
  - Bad programs = not well typed
- Type checking
  - Static typing – most checking at compile time
  - Dynamic typing – most checking at runtime
- Type inference
  - Automatically infer types for a program (or show that there is no valid typing)

Strongly vs. weakly typed

- Coercion
- Strongly typed
  - C, C++, Java
- Weakly typed
  - Perl, PHP
- (YMMV, not everybody agrees on this classification)

Output: 73

perl

```
$a=31;
$b="42x";
$c=$a+$b;
print $c;
```

warning: initialization makes integer from pointer without a cast

C

```
main() {
 int a=31;
 char b[3]="42x";
 int c=a+b;
}
```

error: Incompatible type for declaration. Can't convert java.lang.String to int

Java

```
public class… {
 public static void main() {
 int a=31;
 String b ="42x";
 int c=a+b;
 }
}
```

Last week: how does this magic happen?

- We probably need to go over the AST?
- how does this relate to the clean formalism of the parser?

Syntax Directed Translation

- The parse tree (syntax) is used to drive the translation
- Semantic attributes
  - Attributes attached to grammar symbols
- Semantic actions
  - How to update the attributes when a production is used in a derivation
- Attribute grammars

Attribute grammars

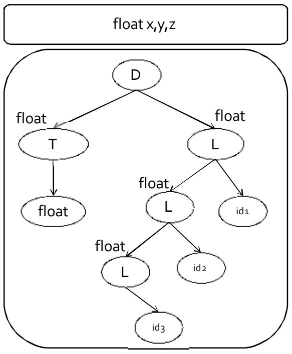
- Attributes
  - Every grammar symbol has attached attributes
    - Example: Expr.type
- Semantic actions
  - Every production rule can define how to assign values to attributes
    - Example:
      Expr → Expr + Term
      Expr.type = Expr1.type when (Expr1.type == Term.type)
      Error otherwise

Indexed symbols

- Add indexes to distinguish repeated grammar symbols
- Does not affect grammar
- Used in semantic actions

- Expr → Expr + Term
  Becomes
  Expr → Expr1 + Term

Example



Production	Semantic Rule
D → T L	L.in = T.type
T → int	T.type = integer
T → float	T.type = float
L → L1, id	L1.in = L.in addType(id.entry,L.in)
L → id	addType(id.entry,L.in)

Attribute Evaluation

- Build the AST
- Fill attributes of terminals with values derived from their representation
- Execute evaluation rules of the nodes to assign values until no new values can be assigned
  - In the right order such that
    - No attribute value is used before its available
    - Each attribute will get a value only once

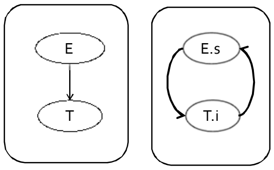
Dependencies

- A semantic equation a = b1,…,bm requires computation of b1,…,bm to determine the value of a

- The value of a depends on b1,…,bm
  - We write a ← bi

Cycles

- Cycle in the dependence graph
- May not be able to compute attribute values



AST

Dependence graph

E.S = T.i
T.i = E.s + 1

Attribute Evaluation

- Build the AST
- Build dependency graph
- Compute evaluation order using topological ordering
- Execute evaluation rules based on topological ordering

- Works as long as there are no cycles

Building Dependency Graph

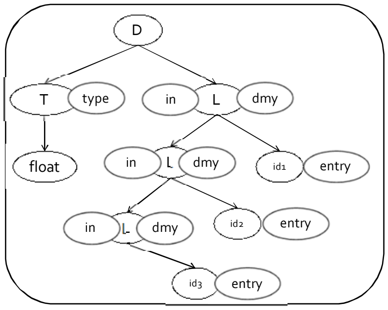
- All semantic equations take the form

  attr1 = func1(attr1.1, attr1.2,…)
  attr2 = func2(attr2.1, attr2.2,…)

- Actions with side effects use a dummy attribute
- Build a directed dependency graph G
  - For every attribute a of a node n in the AST create a node n.a
  - For every node n in the AST and a semantic action of the form b = f(c1,c2,…ck) add edges of the form (ci,b)

Example

float x,y,z



Prod.	Semantic Rule
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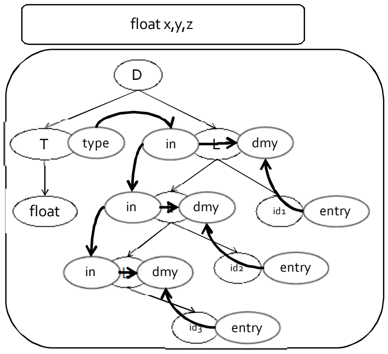
Example



Prod.	Semantic Rule
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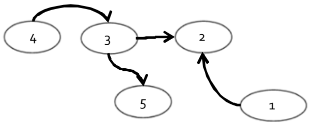
L → id	addType(id.entry,L.in)

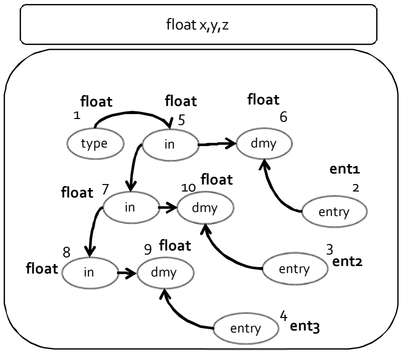
Topological Order

- For a graph G=(V,E), |V|=k
- Ordering of the nodes v1,v2,…vk such that for every edge (vi,vj) ∈ E, i < j



Example topological orderings: 1 4 3 2 5, 4 1 3 5 2

Example



But what about cycles?

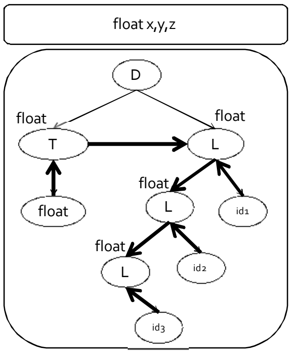
- For a given attribute grammar hard to detect if it has cyclic dependencies
  - Exponential cost
- Special classes of attribute grammars
  - Our "usual trick"
  - sacrifice generality for predictable performance

Inherited vs. Synthesized Attributes

- Synthesized attributes
  - Computed from children of a node
- Inherited attributes
  - Computed from parents and siblings of a node

- Attributes of tokens are technically considered as synthesized attributes

example



Production	Semantic Rule
D → T L	L.in = T.type
T → int	T.type = integer
T → float	T.type = float
L → L_1, id	L_1.in = L.in addType(id.entry,L.in)
L → id	addType(id.entry,L.in)

→ inherited

→ synthesized

S-attributed Grammars

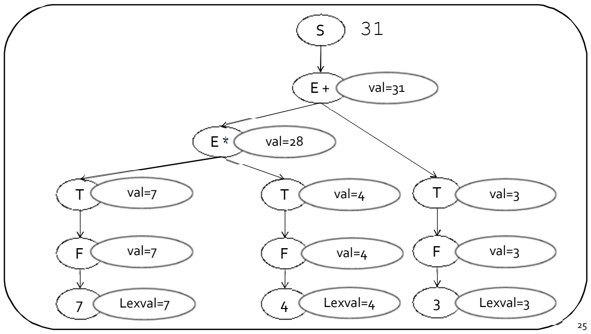
- Special class of attribute grammars
- Only uses synthesized attributes (S-attributed)
- No use of inherited attributes

- Can be computed by any bottom-up parser **during parsing**
- Attributes can be stored on the parsing stack
- Reduce operation computes the (synthesized) attribute from attributes of children

S-attributed Grammar: example

Production	Semantic Rule
S → E ;	print(E.val)
E → E_1 + T	E.val = E_1.val + T.val
E → T	E.val = T.val
T → T_1 * F	T.val = T_1.val * F.val
T → F	T.val = F.val
F → (E)	F.val = E.val
F → digit	F.val = digit.lexval

example



L-attributed grammars

- L-attributed attribute grammar when every attribute in a production A → X1…Xn is
  - A synthesized attribute, or
  - An inherited attribute of Xj, 1 <= j <=n that only depends on
    - Attributes of X1…Xj-1 to the left of Xj, or
    - Inherited attributes of A

Example: typesetting

- Vertical geometry
  - pointsize (ps) – size of letters in a box. Subscript text has smaller point size of 0.7p.
  - baseline
  - height (ht) – distance from top of the box to the baseline
  - depth (dp) – distance from baseline to the bottom of the box.

Example: typesetting

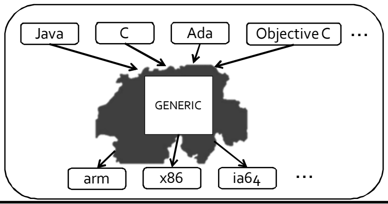
production	semantic rules
S → B	B.ps = 10
B → B1 B2	B1.ps = B.ps B2.ps = B.ps B.ht = max(B1.ht,B2.ht) B.dp = max(B1.dp,B2.dp)
B → B1 sub B2	B1.ps = B.ps B2.ps = 0.7*B.ps B.ht = max(B1.ht,B2.ht – 0.25*B.ps) B.dp = max(B1.dp,B2.dp– 0.25*B.ps)
B → text	B.ht = getHt(B.ps,text.lexval) B.dp = getDp(B.ps,text.lexval)

Attribute grammars: summary

- Contextual analysis can move information between nodes in the AST
  - Even when they are not "local"
- Attribute grammars
  - Attach attributes and semantic actions to grammar
- Attribute evaluation
  - Build dependency graph, topological sort, evaluate
- Special classes with pre-determined evaluation order: S-attributed, L-attributed

Intermediate Representation

- "neutral" representation between the front-end and the back-end
  - Abstracts away details of the source language
  - Abstract away details of the target language
- A compiler may have multiple intermediate representations and move between them
- In practice, the IR may be biased toward a certain language (e.g., GENERIC in gcc)



Intermediate Representation(s)

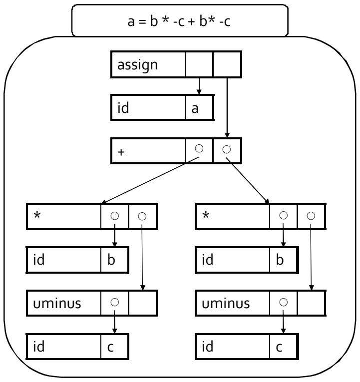
- Annotated abstract syntax tree
- Three address code
- …

Example: Annotated AST

production	semantic rule
S → id := E	S.nptr = makeNode('assign', makeLeaf(id,id.place), E.nptr)
E → E1 + E2	E.nptr = makeNode('+',E1.nptr,E2.nptr)
E → E1 * E2	E.nptr = makeNode('*',E1.nptr,E2.nptr)
E → -E1	E.nptr = makeNode('uminus',E1.nptr)
E → (E1)	E.nptr = E1.nptr
E → id	E.nptr = makeLeaf(id,id.place)

- makeNode – creates new node for unary/binary operator
- makeLeaf – creates a leaf
- id.place – pointer to symbol table

Example

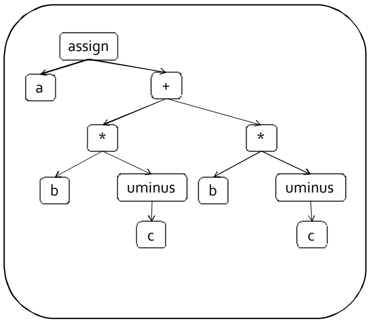


0	id	b	
1	id	c	
2	uminus	1	
3	*	0	2
4	id	b	
5	id	c	
6	uminus	5	
7	*	4	6
8	+	3	7
9	id	a	
10	assign	9	8
11	. . .		

Three Address Code (3AC)

- Every instruction operates on three addresses
  - result = operand1 operator operand2
- Close to low-level operations in the machine language
  - Operator is a basic operation
- Statements in the source language may be mapped to multiple instructions in three address code

Three address code: example



```
t1   :=    - c
t2   :=    b * t1
t3   :=    - c
t4   :=    b * t3
t5   :=    t2 + t4
a    :=    t5
```

Three address code: example instructions

instruction	meaning
x := y op z	assignment with binary operator
x := op y	assignment unary operator
x:= y	assignment
x := &y	assign address of y
x:=*y	assignment from deref y
*x := y	assignment to deref x

instruction	meaning
goto L	unconditional jump
if x relop y goto L	conditional jump

Array operations

- Are these 3AC operations?

x := y[i]

```
t1 := &y      ; t1 = address-of y
t2 := t1 + i  ; t2 = address of y[i]
X  := *t2     ; value stored at y[i]
```

x[i] := y

```
t1 := &x      ; t1 = address-of x
t2 := t1 + i  ; t2 = address of x[i]
*t2:= y       ; store through pointer
```

Three address code: example

```
int main(void) {
  int i;
  int b[10];
  for (i = 0; i < 10; ++i)
    b[i] = i*i;
}
```

```
i := 0                        ; assignment
L1: if i >= 10 goto L2        ; conditional jump
    t0 := i*i
    t1 := &b                  ; address-of operation
    t2 := t1 + i              ; t2 holds the address of b[i]
    *t2 := t0                 ; store through pointer
    i := i + 1
    goto L1
L2:
```

(example source: wikipedia)

Three address code

- Choice of instructions and operators affects code generation and optimization
- Small set of instructions
  - Easy to generate machine code
  - Harder to optimize
- Large set of instructions
  - Harder to generate machine code
- Typically prefer small set and smart optimizer

Creating 3AC

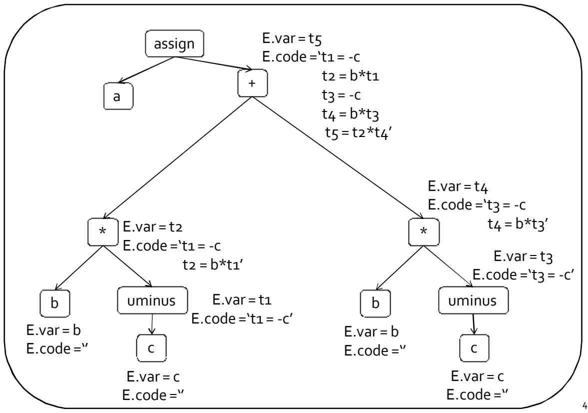
- Assume bottom up parser
  - Why?
- Creating 3AC via syntax directed translation
- Attributes
  - code – code generated for a nonterminal
  - var – name of variable that stores result of nonterminal
- freshVar – helper function that returns the name of a fresh variable

Creating 3AC: expressions

production	semantic rule
S ⟶ id := E	S.code := E. code || gen(id.var ‘:=‘ E.var)
E ⟶ E1 + E2	E.var := freshVar(); E.code = E1.code || E2.code || gen(E.var ‘:=‘ E1.var ‘+’ E2.var)
E ⟶ E1 * E2	E.var := freshVar(); E.code = E1.code || E2.code || gen(E.var ‘:=‘ E1.var ‘*’ E2.var)
E ⟶ - E1	E.var := freshVar(); E.code = E1.code || gen(E.var ‘:=‘ ‘uminu’ E1.var)
E ⟶ (E1)	E.var := E1.var E.code = ‘(‘ || E1.code || ‘)’
E ⟶ id	E.var := id.var; E.code = ‘’

(we use || to denote concatenation of intermediate code fragments)

example

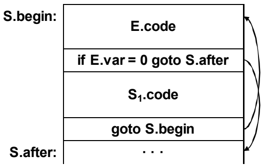


Creating 3AC: control statements

- 3AC only supports conditional/unconditional jumps
- Add labels
- Attributes
  - begin – label marks beginning of code
  - after – label marks end of code
- Helper function freshLabel() allocates a new fresh label

Creating 3AC: control statements

S ⟶ while E do S1



production	semantic rule
S ⟶ while E do S1	S.begin := freshLabel(); S.after = freshLabel(); S.code := gen(S.begin ‘:’) || E.code || gen(‘if’ E.var ‘=‘ ‘o’ ‘goto’ S.after) || S1.code || gen(‘goto’ S.begin) || gen(S.after ‘:’)

Representing 3AC

- Quadruple (op,arg1,arg2,result)
- Result of every instruction is written into a new temporary variable
- Generates many variable names
- Can move code fragments without complicated renaming
- Alternative representations may be more compact

```
t1 = - c
t2 = b * t1
t3 = - c
t4 = b * t3
t5 = t2 * t4
a = t5
```

	op	arg 1	arg 2	result
(0)	uminus	c		t_1
(1)	*	b	t_1	t_2
(2)	uminus	c		t_3
(3)	*	b	t_3	t_4
(4)	+	t_2	t_4	t_5
(5)	:=	t_5		a

Allocating Memory

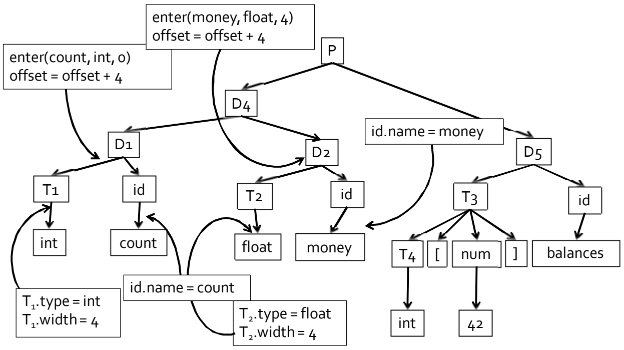
- Type checking helped us guarantee correctness
- Also tells us
  - How much memory allocate on the heap/stack for varaibles
  - Where to find variables (based on offsets)
  - Compute address of an element inside array (size of stride based on type of element)

Allocating Memory

- Global variable "offset" with memory allocated so far

production	semantic rule
P → D	{ offset := 0}
D → D D	
D → T id;	{ enter(id.name, T.type, offset); offset += T.width }
T → integer	{ T.type := int; T.width = 4 }
T → float	{ T.type := float; T.width = 8}
T → T1[num]	{ T.type = array (num.val,T1.Type); T.width = num.val * T1.width; }
T → *T1	{ T.type := pointer(T1.type); T.width = 4}

Allocating Memory



Adjusting to bottom-up

production	semantic rule
P → **M** D	
M → ε	**{ offset := 0}**
D → D D	
D → T id;	{ enter(id.name, T.type, offset); offset += T.width }
T → integer	{ T.type := int; T.width = 4 }
T → float	{ T.type := float; T.width = 8}
T → T1[num]	{ T.type = array (num.val,T1.Type); T.width = num.val * T1.width; }
T → *T1	{ T.type := pointer(T1.type); T.width = 4}

Generating IR code

- Option 1
  accumulate code in AST attributes
- Option 2
  emit IR code to a file during compilation
  - If for every production the code of the left-hand-side is constructed from a concatenation of the code of the RHS in some fixed order

Expressions and assignments

production	semantic action
S → id := E	{ p:= lookup(id.name); if p ≠ null then **emit**(p ':=' E.var) else error }
E → E1 op E2	{ E.var := freshVar(); **emit**(E.var ':=' E1.var op E2.var) }
E → - E1	{ E.var := freshVar(); **emit**(E.var ':=' 'uminus' E1.var) }
E → (E1)	{ E.var := E1.var }
E → id	{ p:= lookup(id.name); if p ≠ null then E.var :=p else error }

Boolean Expressions

production	semantic action
E → E1 op E2	{ E.var := freshVar(); **emit**(E.var ':=' E1.var op E2.var) }
E → not E1	{ E.var := freshVar(); **emit**(E.var ':=' 'not' E1.var) }
E → (E1)	{ E.var := E1.var }
E → true	{ E.var := freshVar(); **emit**(E.var ':=' '1') }
E → false	{ E.var := freshVar(); **emit**(E.var ':=' '0') }

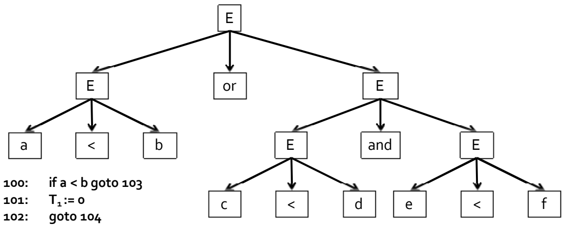
- Represent true as 1, false as 0
- Wasteful representation, creating variables for true/false

Boolean expressions via jumps

production	**semantic action**

E → id1 op id2	{
	E.var := freshVar();
	emit(‘if’ id1.var relop id2.var‘goto’ nextStmt+2);
	emit(E.var ‘:=‘ ‘0’);
	emit(‘goto ‘ nextStmt + 1);
	emit(E.var ‘:=‘ ‘1’)
	}

Example



100: **if a < b goto 103**
101: **T_1 := 0**
102: **goto 104**
103: **T_1 := 1**

104: **if c < d goto 107**
105: **T_2 := 0**
106: **goto 108**
107: **T_2 := 1**

108: **if e < f goto 111**
109: **T_3 := 0**
110: **goto 112**
111: **T_3 := 1**
112: **T_4 := T_2 and T_3**
113: **T_5 := T_1 or T_4**

Short circuit evaluation

- Second argument of a boolean operator is only evaluated if the first argument does not already determine the outcome
- (x and y) is equivalent to
  if x then y else false;
- (x or y) is equivalent to
  if x then true else y

example

a < b or (c<d and e<f)

100: if a < b goto 103
101: T_1 := 0
102: goto 104
103: T_1 := 1
104: if c < d goto 107
105: T_2 := 0
106: goto 108
107: T_2 := 1
108: if e < f goto 111
109: T_3 := 0
110: goto 112
111: T_3 := 1
112: T_4 := T_2 and T_3
113: T_5 := T_1 and T_4

naive

100: if a < b goto 105
101: if !(c < d) goto 103
102: if e < f goto 105
103: T := 0
104: goto 106
105: T := 1
106:

Short circuit evaluation

More examples

```
int denom = 0;
if (denom && nom/denom) {
        oops_i_just_divided_by_zero();
}
```

```
int x=0;
if (++x>0 && x==1) {
        hmmm();
}
```

Summary

- Three address code (3AC)
- Generating 3AC
- Boolean expressions
- Short circuit evaluation

Next time

- Generating IR for control structures
    - While, for, if
- backpatching

The End