COP4020 Programming Languages

Semantics

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Overview

- Static semantics
- Dynamic semantics
- Attribute grammars
- Abstract syntax trees

Static Semantics

- *Syntax* concerns the form of a valid program, while *semantics* concerns its meaning
  - Context-free grammars are not powerful enough to describe certain rules, e.g. checking variable declaration with variable use
- *Static semantic* rules are enforced by a compiler at compile time
  - Implemented in semantic analysis phase of the compiler
- Examples:
  - Type checking
  - Identifiers are used in appropriate context
  - Check subroutine call arguments
  - Check labels

Dynamic Semantics

- *Dynamic semantic* rules are enforced by the compiler by generating code to perform the checks at run-time
- Examples:
  - Array subscript values are within bounds
  - Arithmetic errors
  - Pointers are not dereferenced unless pointing to valid object
  - A variable is used but hasn't been initialized
- Some languages (Euclid, Eiffel) allow programmers to add explicit dynamic semantic checks in the form of assertions, e.g.

```
assert denominator not= 0
```

- When a check fails at run time, an exception is raised

Attribute Grammars

- An attribute grammar “connects” syntax with semantics
- Each grammar production has a *semantic rule* with *actions* (e.g. assignments) to modify values of *attributes* of (non)terminals
  - A (non)terminal may have any number of attributes
  - Attributes have values that hold information related to the (non)terminal
- General form:

production	**semantic rule**
<*A*> ::= <*B*> <*C*>	*A*.a := ...; *B*.a := ...; *C*.a := ...

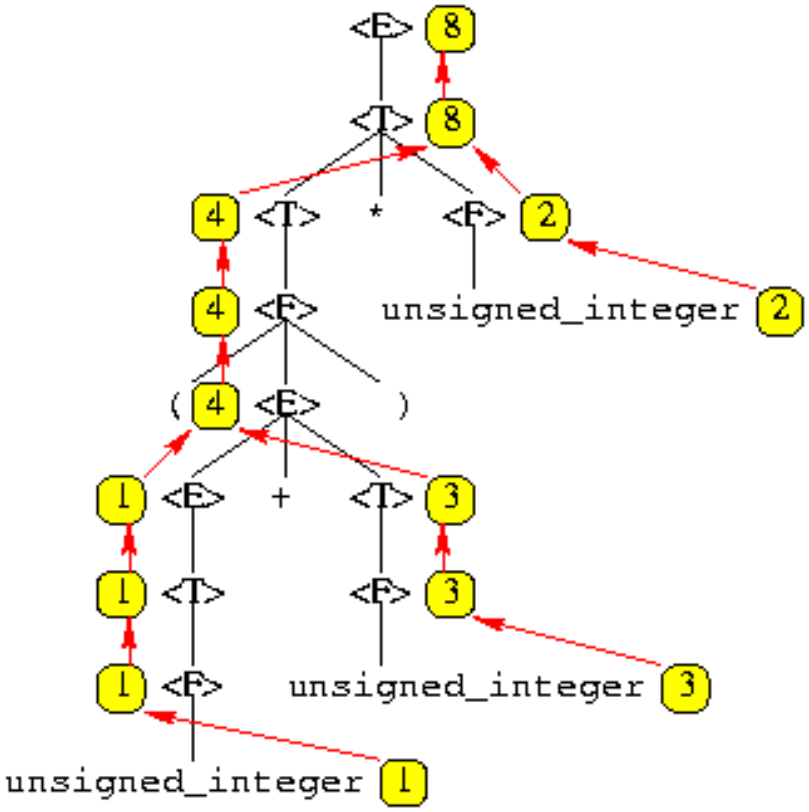
- Semantic rules are used by a compiler to enforce static semantics and/or to produce an abstract syntax tree while parsing tokens
- Can also be used to build simple language interpreters

Example Attributed Grammar

- The val attribute of a (non)terminal holds the subtotal value of the subexpression
- Nonterminals are indexed in the attribute grammar to distinghuish multiple occurrences of the nonterminal in a production

production		**semantic rule**
$<E_1>$	::= $<E_2>$ + $<T>$	E_1.val := E_2.val + T.val
$<E_1>$	::= $<E_2>$ - $<T>$	E_1.val := E_2.val - T.val
$<E>$	::= $<T>$	E.val := T.val
$<T_1>$	::= $<T_2>$ * $<F>$	T_1.val := T_2.val * F.val
$<T_1>$	::= $<T_2>$ / $<F>$	T_1.val := T_2.val / F.val
$<T>$	::= $<F>$	T.val := F.val
$<F_1>$	::= - $<F_2>$	F_1.val := -F_2.val
$<F>$	::= ($<E>$)	F.val := E.val
$<F>$	::= unsigned_int	F.val := unsigned_int.val

Decorated Parse Trees

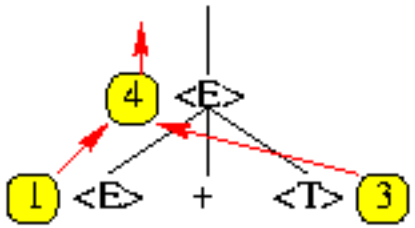


- A parser produces a parse tree that is *decorated* with the attribute values
- Example decorated parse tree of **(1+3)*2** with the val attributes

Synthesized Attributes

- *Synthesized attributes* of a node hold values that are computed from attribute values of the *child* nodes in the parse tree and therefore information flows upwards

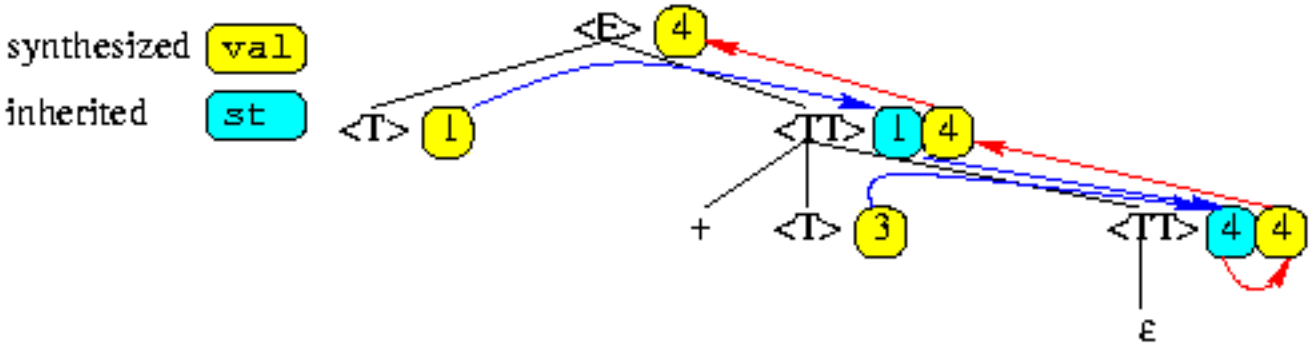
production	**semantic rule**
$<E_1>$ ::= $<E_2>$ + $<T>$	E_1.val := E_2.val + T.val



Inherited Attributes

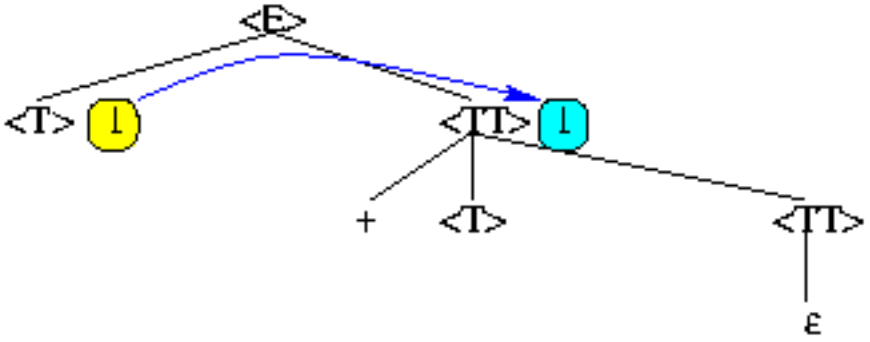
- *Inherited attributes* of *child* nodes are set by the *parent* node and therefore information flows downwards

production		**semantic rule**
<*E*>	::= <*T*> <*TT*>	*TT*.st := *T*.val; *E*.val := *TT*.val
<TT_1>	::= + <*T*> <TT_2>	TT_2.st := TT_1.st + *T*.val; TT_1.val := TT_2.val
<*TT*>	::= ε	*TT*.val := *TT*.st



Attribute Flow

- An *attribute flow algorithm* propagates attribute values through the parse tree by traversing the tree according to the *set* (write) and *use* (read) dependencies (an attribute must be set before it is used)



production	**semantic rule**
<*E*> ::= <*T*> <*TT*>	*TT*.st := *T*.val

Attribute Flow

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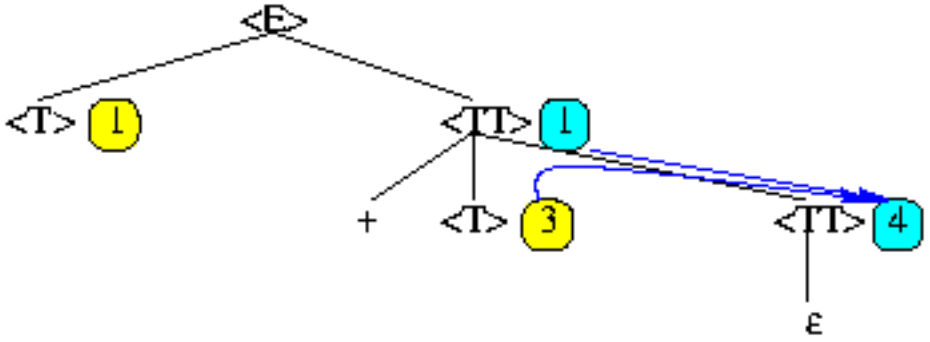

production	**semantic rule**
$<TT_1>$ ::= + $<T>$ $<TT_2>$	TT_2.st := TT_1.st + T.val

Attribute Flow

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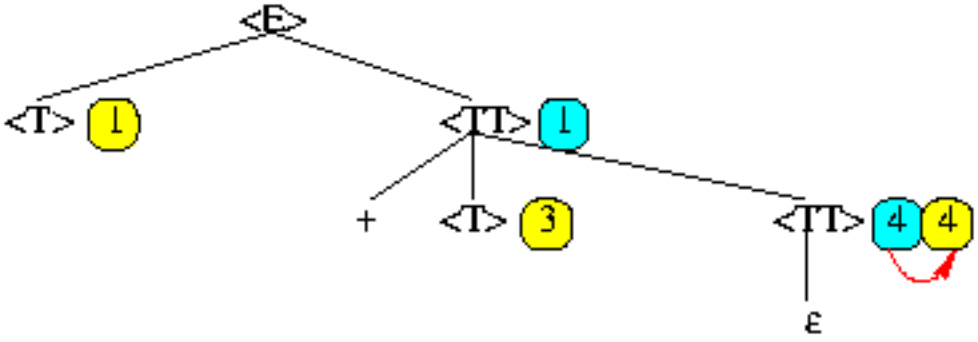

production	**semantic rule**
<*TT*> ::= ε	*TT*.val := *TT*.st

Attribute Flow

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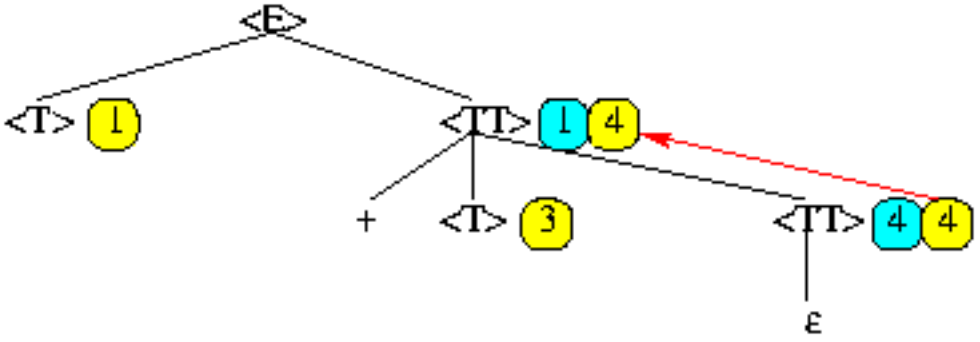
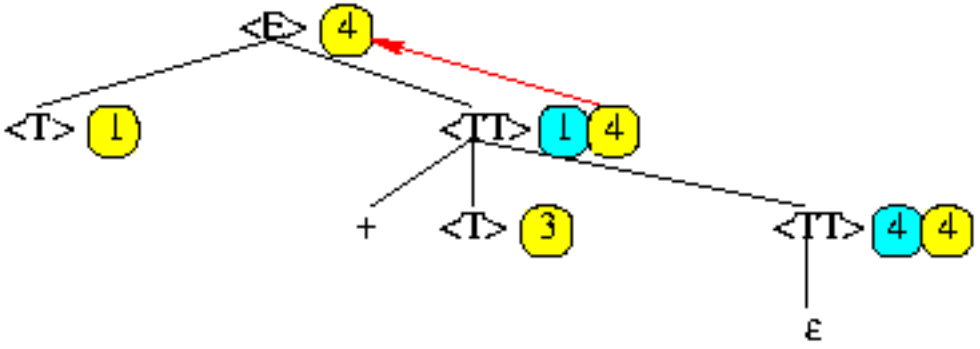


production	**semantic rule**
$<TT_1>$ ::= + $<T>$ $<TT_2>$	TT_1.val := TT_2.val

Attribute Flow

- An *attribute flow algorithm* propagates attribute values through the parse tree by traversing the tree according to the *set* (write) and *use* (read) dependencies (an attribute must be set before it is used)



production	**semantic rule**
<*E*> ::= <*T*> <*TT*>	*E*.val := *TT*.val

S- and L-Attributed Grammars

- A grammar is called *S-attributed* if all attributes are synthesized
- A grammar is called *L-attributed* if the parse tree traversal to update attribute values is always left-to-right and depth-first
  - Synthesized attributes always OK
  - Values of inherited attributes must be passed down to children from left to right
  - Semantic rules can be applied immediately during parsing and parse trees do not need to be kept in memory
  - This is an essential grammar property for a one-pass compiler
- An S-attributed grammar is a special case of an L-attributed grammar

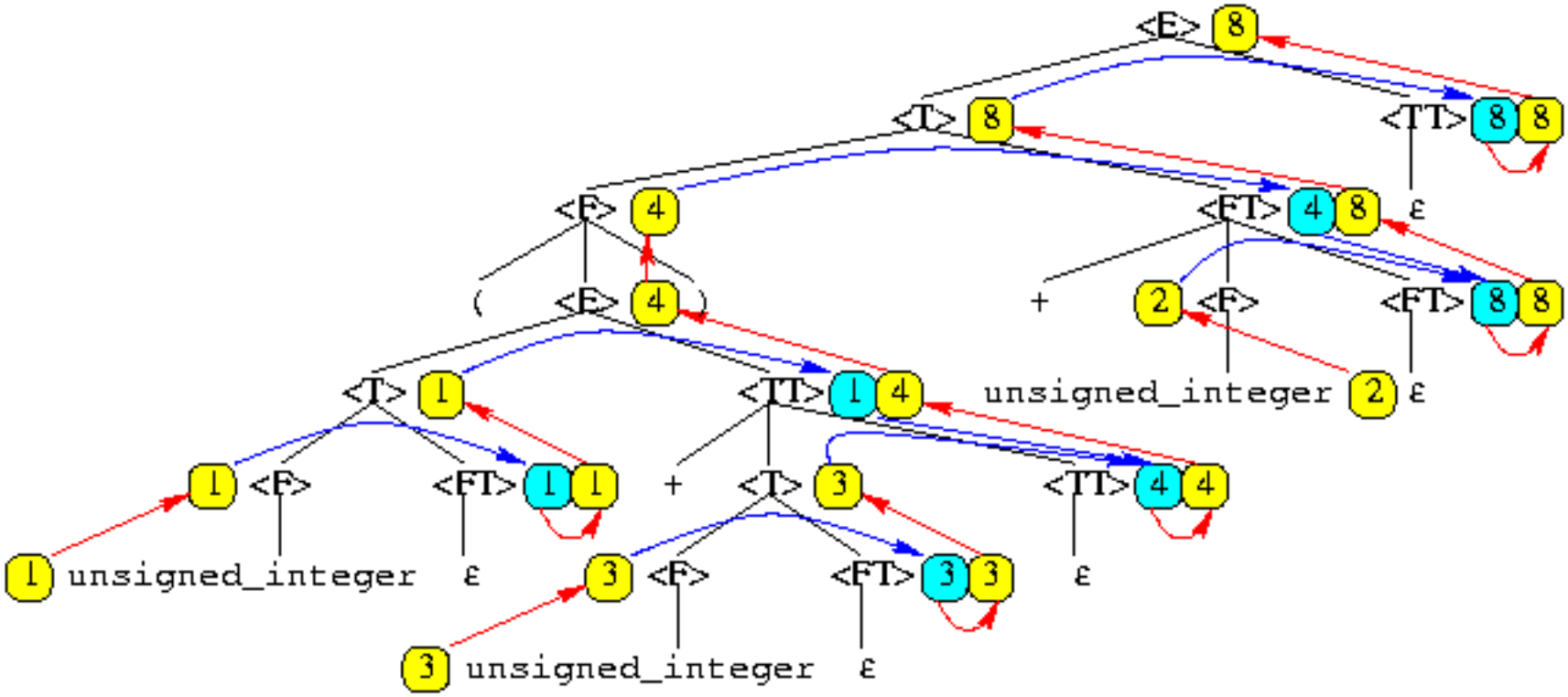
Example L-Attributed Grammar

- Implements a calculator

production		**semantic rule**
<*E*>	::= <*T*> <*TT*>	*TT*.st := *T*.val; *E*.val := *TT*.val
<TT_1>	::= + <*T*> <TT_2>	TT_2.st := TT_1.st + *T*.val; TT_1.val := TT_2.val
<TT_1>	::= - <*T*> <TT_2>	TT_2.st := TT_1.st - *T*.val; TT_1.val := TT_2.val
<*TT*>	::= ε	*TT*.val := *TT*.st
<*T*>	::= <*F*> <*FT*>	*FT*.st := *F*.val; *T*.val := *FT*.val
<FT_1>	::= * <*F*> <FT_2>	FT_2.st := FT_1.st * *F*.val; FT_1.val := FT_2.val
<FT_1>	::= / <*F*> <FT_2>	FT_2.st := FT_1.st / *F*.val; FT_1.val := FT_2.val
<*FT*>	::= ε	*FT*.val := *FT*.st
<F_1>	::= - <F_2>	F_1.val := -F_2.val
<*F*>	::= (<*E*>)	*F*.val := *E*.val
<*F*>	::= unsigned_int	*F*.val := unsigned_int.val

Example Decorated Parse Tree

- Fully decorated parse tree of **(1+3)*2**



Recursive Descent Parsing with L-Attributed Grammars

- Semantic rules are added to the bodies of the recursive descent functions and placed appropriately between the function calls

- Inherited attribute values are input arguments to the functions
  - Argument passing flows downwards in call graphs
- Synthesized attribute values are returned by functions
  - Return values flow upwards in call graphs

Example

production	semantic rule
<*E*> ::= <*T*> <*TT*>	*TT*.st := *T*.val; *E*.val := *TT*.val
<TT_1> ::= + <*T*> <TT_2>	TT_2.st := TT_1.st + *T*.val; TT_1.val := TT_2.val
<TT_1> ::= - <*T*> <TT_2>	TT_2.st := TT_1.st - *T*.val; TT_1.val := TT_2.val
<*TT*> ::= ε	*TT*.val := *TT*.st

```
procedure E()
  Tval = T();
  Eval = TT(Tval);
  return Eval;
procedure TT(TTst)
  case (input_token())
  of '+': match('+');
          Tval = T();
          TTval = TT(TTst + Tval);
 of '-': match('-');
          Tval = T();
          TTval = TT(TTst - Tval);
  otherwise: TTval = TTst;
  return TTval;
```

Constructing Abstract Syntax Trees with Attribute Grammars

- Three operations to create nodes for an AST tree that represents expressions:
  - *mk_bin_op*(*op*, *left*, *right*): constructs a new node that contains a binary operator *op* and AST sub-trees *left* and *right* representing the operator's operands and returns pointer to the new node
  - *mk_un_op*(*op*, *node*): constructs a new node that contains a unary operator *op* and sub-tree *node* representing the operator's operand and returns pointer to the new node
  - *mk_leaf*(*value*): constructs an AST leaf that contains a value and returns pointer to the new node

An L-Attributed Grammar to Construct ASTs

- Semantic rules to build up an AST

production		**semantic rule**
<*E*>	::= <*T*> <*TT*>	*TT*.st := *T*.ptr; *E*.ptr := *TT*.ptr
<TT_1>	::= + <*T*> <TT_2>	*TT*2.st := *mk_bin_op*("+", TT_1.st, *T*.ptr); TT_1.ptr := TT_2.p
<TT_1>	::= - <*T*> <TT_2>	*TT*2.st := *mk_bin_op*("-", TT_1.st, *T*.ptr); TT_1.ptr := TT_2.pt
<*TT*>	::= ε	*TT*.ptr := *TT*.st
<*T*>	::= <*F*> <*FT*>	*FT*.st := *F*.ptr; *T*.ptr := *FT*.ptr
<FT_1>	::= * <*F*> <FT_2>	FT_2.st := *mk_bin_op*("*", FT_1.st, *F*.ptr); FT_1.ptr := FT_2.pt
<FT_1>	::= / <*F*> <FT_2>	FT_2.st := *mk_bin_op*("/", FT_1.st, *F*.ptr); FT_1.ptr := FT_2.pt
<*FT*>	::= ε	*FT*.ptr := *FT*.st
<F_1>	::= - <F_2>	F_1.ptr := *mk_un_op*("-", F_2.ptr)
<*F*>	::= (<*E*>)	*F*.ptr := *E*.ptr
<*F*>	::= unsigned_int	*F*.ptr := *mk_leaf*(unsigned_int.val)

Example Decorated Parse Tree with AST

- Decorated parse tree of **(1+3)*2** with AST