Semantic actions for declarations and expressions

Semantic actions

- *Semantic actions* are routines called as productions (or parts of productions) are recognized
- Actions work together to build up intermediate representations

  <if-stmt> → IF <expr> #startif THEN <stmts> END #endif

  - Semantic action for #startif needs to pass a *semantic record* to #endif

Semantic Records

- Data structures produced by semantic actions
- Associated with both non-terminals (code structures) and terminals (tokens/symbols)
  - Do not have to exist (e.g., no action associated with ";")
- Control statements often require multiple actions (see <if-stmt> example on previous slide)
- Typically: semantic records are produced by actions associated with terminals, and are passed to actions associated with non-terminals, which combine them to produce new semantic records
- Standard organization: *semantic stack*

How do we manipulate stack?

- *Action-controlled*: actions directly manipulate stack (call push and pop)
- *Parser-controlled*: parser automatically manipulates stack

LR-parser controlled

- Shift operations push semantic records onto stack (describing the token)
- Reduce operations pop semantic records associated with symbols off stack, replace with semantic record associated with production
- Action routines do not see stack. Can refer to popped off records using handles
    - e.g., in yacc/bison, use $1, $2 etc. to refer to popped off records

Example of semantic actions

- Consider following grammar:

assign → ident := expr
expr → term addop term
term → ident | LIT
ident → ID
addop → + | –

Example of semantic actions

- In Bison (note that lexer returns values for each token through yylval)

```
assign  → ident := expr {$$ = generateAssign($1, $3);}
expr    → term addop term {$$ = generateExpr($1, $2, $3);}
term    → ident {$$ = generateTerm($1);} |
           LIT {$$ = generateTerm($1);}
ident   → ID {$$ = $1;}
addop   → + {$$ = ADD_OP;} | – {$$ = SUB_OP;}
```

Example of semantic stack

- Consider a := b + 1;

LL-controlled

- Parse stack contains predicted productions, not matched productions
- Push empty semantic records onto stack when production is predicted
- Fill in records as symbols are matched
- When non-terminal is matched, pop off records associated with RHS, use to fill in the record associated with LHS (leave LHS record on stack)

Example of semantic actions

- In ANTLR:

```
assign returns [Code c]
    → ident := expr {$c = generateCode($ident.name, $expr.c);}
expr returns [Code c]
    → t1=term addop t2=term {
        $c = generateCode($t1.t, $t2.t, $addop.opType);
        }
term returns [Term t]
    → ident {$t = generateTerm($ident.s);}
    | LIT {$t = generateTerm($LIT.text);}
ident returns [String s] → ID {$s = $ID.text;}
addop returns [OpType opType]
    → + {$opType = ADD_OP;} | – {$opType = SUB_OP;}
```

Overview of declarations

- Symbol tables
- Action routines for simple declarations
- Action routines for advanced features
  - Constants
  - Enumerations
  - Arrays
  - Structs
  - Pointers

Symbol Tables

- Table of declarations, associated with each scope
  - Internal structure used by compiler – does not become code
- One entry for each variable declared
  - Store declaration *attributes* (e.g., name and type) – will discuss this in a few slides
- Table must be dynamic (why?)
- Possible implementations
  - Linear list (easy to implement, only good for small programs)
  - Binary search trees (better for large programs, but can still be slow)
  - Hash tables (best solution)

Managing symbol tables

- Maintain list of all symbol tables
- Maintain stack marking "current" symbol table
- Whenever you see a program block that allows declarations, create a new symbol table
    - Push onto stack as "current" symbol table
- When you see declaration, add to current symbol table
- When you exit a program block, pop current symbol table off stack

Handling declarations

- Declarations of variables, arrays, functions, etc.
  - Create entry in symbol table
  - Allocate space in *activation record*
    - Activation record stores information for a particular function call (arguments, return value, local variables, etc.)
      - Need to have space for all of this information
    - Activation record stored on program stack
    - We will discuss these in more detail when we get to functions

Simple declarations

- Declarations of simple types

  ```
  INT x;

  FLOAT f;
  ```

- Semantic action should
  - Get the type and name of identifier
  - Check to see if identifier is already in the symbol table
    - If it isn't, add it, if it is, error

Simple declarations (cont.)

- How do we get the type and name of an identifier?

```
var_decl → var_type id;

var_type → INT | FLOAT

id → IDENTIFIER
```

- Where do we put the semantic actions?

Simple declarations (cont.)

- How do we get the type and name of an identifier?

```
var_decl → var_type id; #decl_id

var_type → INT #int_type | FLOAT #float_type

id → IDENTIFIER #id
```

- Where do we put the semantic actions?
  - When we process #int_type and #id, can store the type and identifier name and pass them to #decl_id
- When creating activation record, allocate space based on type (why?)

Constants

- Constants
  - Symbol table needs a field to store constant value
  - In general, the constant value may not be known until runtime (`static final int i = 2 + j;`)
  - At compile time, we create code that allows the initialization expression to assign to the variable, then evaluate the expression at run-time

Arrays

- Fixed size (static) arrays

  `int A[10];`

  - Store type and length of array
  - When creating activation record, allocate enough space on stack for array

- What about variable size arrays?

  `int A[M][N]`

  - Store information for a *dope vector*
    - Tracks dimensionality of array, size, location
    - Activation record stores dope vector
    - At runtime, allocate array at top of stack, fill in dope vector

Defining new types

- Some declarations define new types!
  - Enums, structs, classes
- This information must be stored in the symbol table, too (Why?)

Enums

- Enumeration types: `enum days {mon, tue, wed, thu, fri, sat, sun};`
  - Create an entry for the enumeration type itself, and an entry for each member of the enumeration
    - Entries are usually linked
  - Processing enum declaration sets the "enum counter" to lower bound (usually 0)
  - Each new member seen is assigned the next value and the counter is incremented
    - In some languages (*e.g.*, C), enum members may be assigned particular values. Should ensure that enum value isn't reused

Structs/classes

- Can have variables/methods declared inside, need extra symbol table
  - Need to store visibility of members
- Complication: can create multiple instances of a struct or class!
  - Need to store *offset* of each member in struct

Pointers

- Need to store type information and length of what it points to
  - Needed for pointer arithmetic

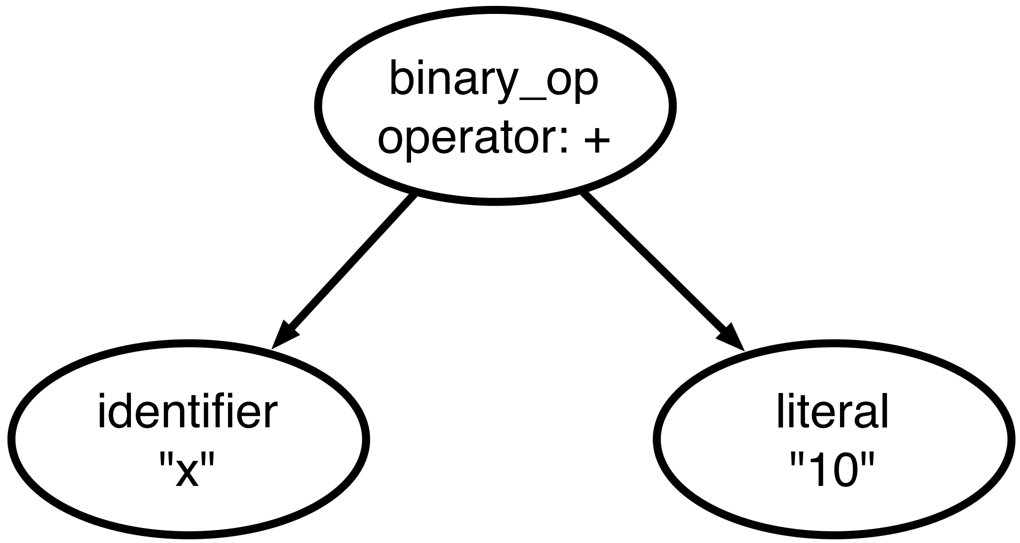
    ```
    int * a = &y;
    z = *(a + 1);
    ```

- Need to worry about forward declarations
  - The thing being pointed to may not have been declared yet

    ```
    Class Foo;
    Foo * head;
    Class Foo { ... };
    ```

Abstract syntax trees

- Tree representing structure of the program
  - Built by semantic actions
  - Some compilers skip this
- AST nodes
  - Represent program construct
  - Store important information about construct



ASTs for References

Referencing identifiers

- Different behavior if identifier is used in a declaration vs. expression
  - If used in declaration, treat as before
  - If in expression, need to:
    - Check if it is symbol table
    - Create new AST node with pointer to symbol table entry
    - Note: may want to directly store type information in AST (or could look up in symbol table each time)

Referencing Literals

- What about if we see a literal?

  primary → INTLITERAL | FLOATLITERAL

- Create AST node for literal
- Store string representation of literal
  - "155", "2.45" etc.
- At some point, this will be converted into actual representation of literal
  - For integers, may want to convert early (to do *constant folding*)
  - For floats, may want to wait (for compilation to different machines). Why?

More complex references

- Arrays
  - A[i][j] is equivalent to

    `A + i*dim_1 + j`
  - Extract `dim_1` from symbol table or dope vector
- Structs
  - A.f is equivalent to

    `&A + offset(f)`
  - Find `offset(f)` in symbol table for declaration of record
- Strings
  - Complicated–depends on language

Expressions

- Three semantic actions needed
    - eval_binary (processes binary expressions)
        - Create AST node with two children, point to AST nodes created for left and right sides
    - eval_unary (processes unary expressions)
        - Create AST node with one child
    - process_op (determines type of operation)
        - Store operator in AST node

Expressions example

- $x + y + 5$

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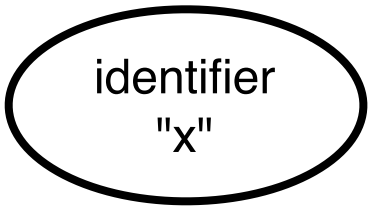

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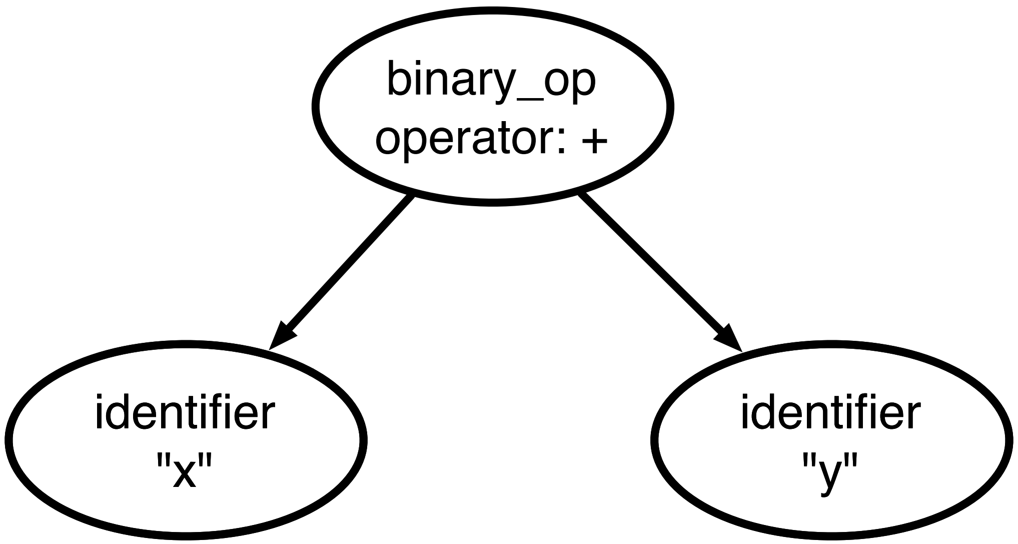

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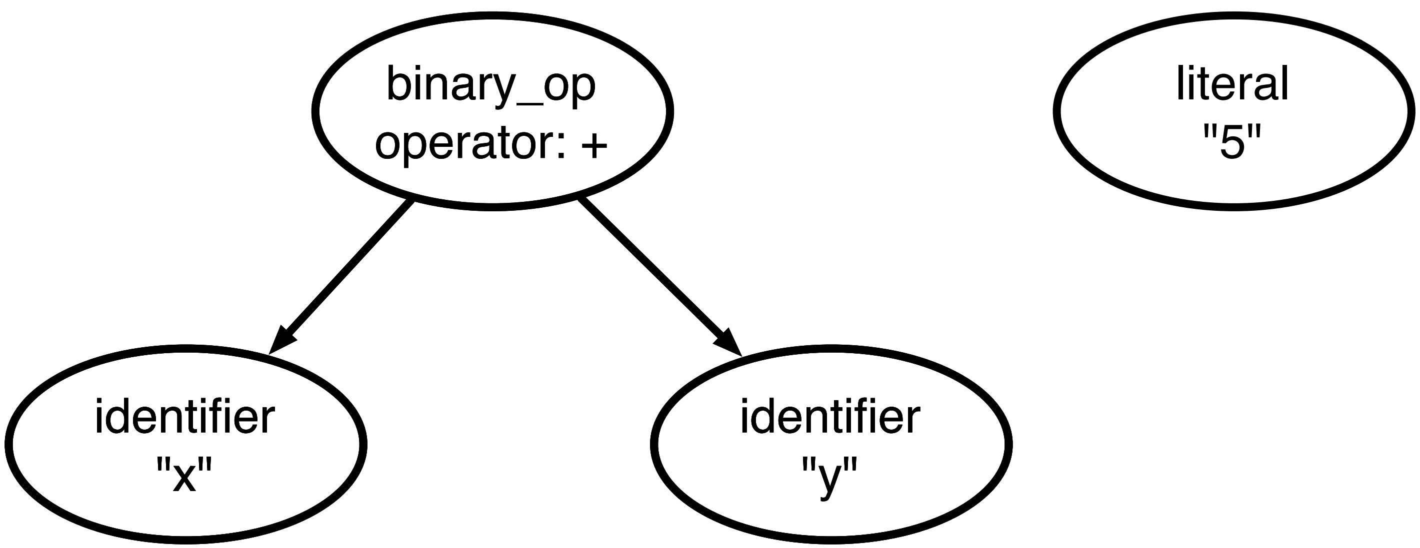

Expressions example

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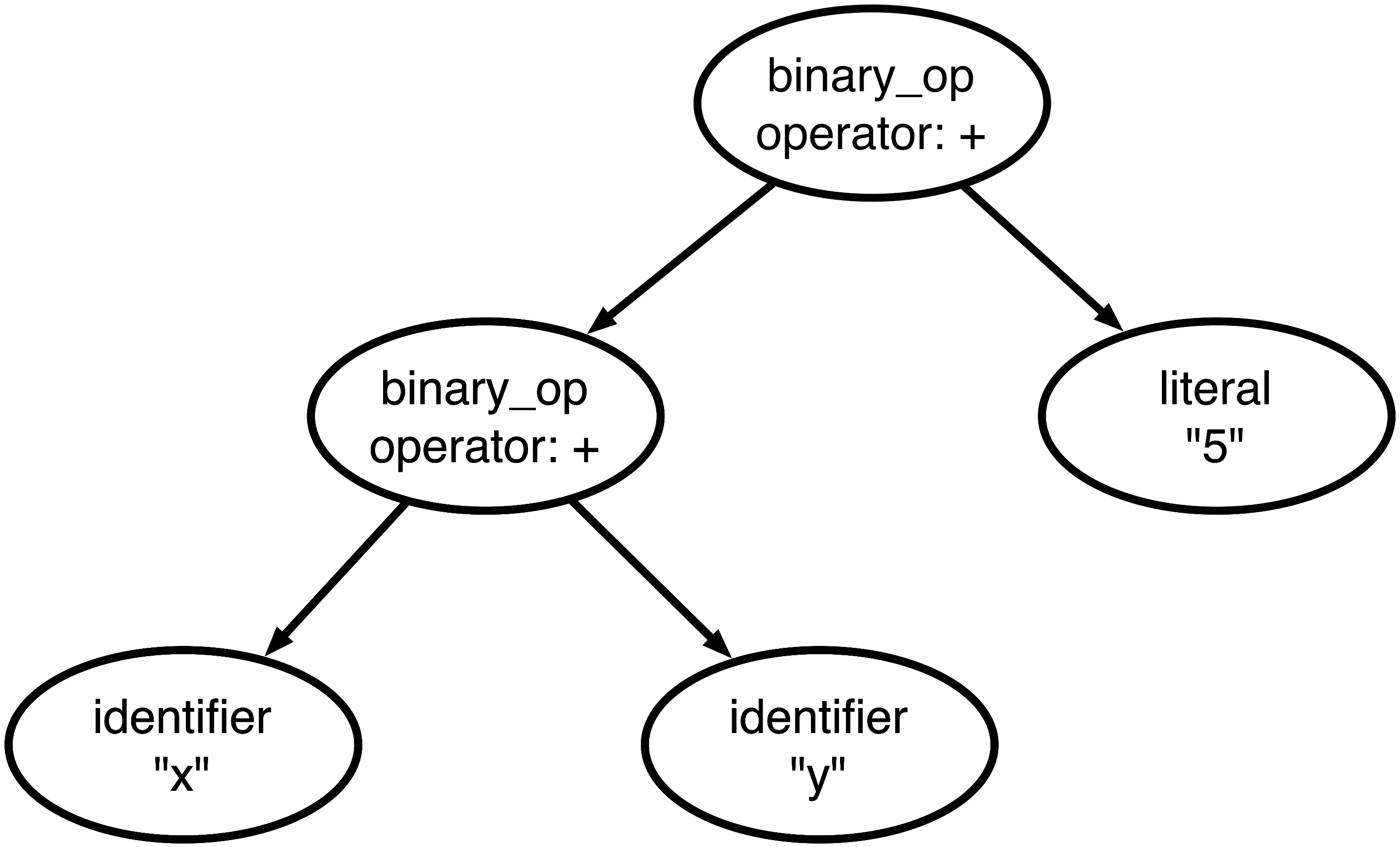

Generating three-address code

- For project, will need to generate three-address code
  - op A, B, C //C = A op B
- Can do this directly or after building AST

Generating code from an AST

- Do a post-order walk of AST to generate code, pass generated code up

```
data_object generate_code() {
  //pre-processing code
  data_object lcode = left.generate_code();
  data_object rcode = right.generate_code();
  return generate_self(lcode, rcode);
}
```

- Important things to note:
  - A node generates code for its children before generating code for itself
  - Data object can contain code or other information
  - Code generation is *context free*
    - What does this mean?

Generating code directly

- Generating code directly using semantic routines is very similar to generating code from the AST
  - Why?
  - Because post-order traversal is essentially what happens when you evaluate semantic actions as you pop them off stack
  - AST nodes are just semantic records
- To generate code directly, your semantic records should contain structures to hold the code as it's being built

Data objects

- Records various important info
  - The temporary storing the result of the current expression
  - Flags describing value in temporary
    - Constant, L-value, R-value
  - Code for expression

L-values vs. R-values

- L-values: addresses which can be stored to or loaded from
- R-values: data (often loaded from addresses)
  - Expressions operate on R-values
- Assignment statements:

  `L-value := R-value`

- Consider the statement `a := a`
  - the `a` on LHS refers to the memory location referred to by `a` and we store to that location
  - the `a` on RHS refers to data *stored in* memory location referred to by `a` so we will load from that location to produce the R-value

Temporaries

- Can be thought of as an unlimited pool of registers (with memory to be allocated at a later time)
- Need to declare them like variables
- Name should be something that cannot appear in the program (*e.g.*, use illegal character as prefix)
- Memory must be allocated if address of temporary can be taken (e.g. $a := \&b$)
- Temporaries can hold either L-values or R-values

Simple cases

- Generating code for constants/literals
  - Store constant in temporary
  - Optional: pass up flag specifying this is a constant
- Generating code for identifiers
  - Generated code depends on whether identifier is used as L-value or R-value
    - Is this an address? Or data?
  - One solution: just pass identifier up to next level
    - Mark it as an L-value (it's not yet data!)
    - Generate code once we see how variable is used

Generating code for expressions

- Create a new temporary for result of expression
- Examine data-objects from subtrees
- If temporaries are L-values, load data from them into new temporaries
    - Generate code to perform operation
    - In project, no need to explicitly load
- If temporaries are constant, can perform operation immediately
    - No need to perform code generation!
- Store result in new temporary
    - Is this an L-value or an R-value?
- Return code for entire expression

Generating code for assignment

- Store value of temporary from RHS into address specified by temporary from LHS
  - Why does this work?
  - Because temporary for LHS holds an address
    - If LHS is an identifier, we just stored the address of it in temporary
    - If LHS is complex expression

      ```
      int *p = &x
      ```

      ```
      *(p + 1) = 7;
      ```

      it *still* holds an address, even though the address was computed by an expression

Pointer operations

- So what do pointer operations do?
- Mess with L and R values
- & (address of operator): take L-value, and treat it as an R-value (without loading from it)

```
x = &a + 1;
```

- * (dereference operator): take R-value, and treat it as an L-value (an address)

```
*x = 7;
```