CS 432
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```
public class WhileLoopCounter extends
    private int numWhileLoops = 0;
    @Override
    public void preVisit(ASTWhileLoop
    {
        numWhileLoops++;
    }
    @Override
    public void postVisit(ASTProgram
    {
        System.out.println("Number of
                numWhileLoops);
    }
}
```

Type Systems and the Visitor Design Pattern

General theme

- *Pattern matching* over a tree is very useful in compilers
  - Debug output (P3)
  - **Type checking & other static analysis (P4)**
  - Code generation (P5)
  - Instruction selection
- Theory and practice
  - Type systems describe correctly-typed program trees
  - Visitor design pattern allows clean implementation in a non-functional language
    - Generalization of tree traversal (CS 240 approach)

Types

- A type is an abstract category characterizing a range of data values
  - Base types: integer, character, boolean, floating-point
  - Enumerated types (finite list of constants)
  - Pointer types (“address of X”)
  - Array or list types (“list of X”)
  - Compound/record types (named collections of other types)
  - Function types: (type1, type2, type3) → type4

Type Systems

- A type system is a set of type rules
  - Rules: valid types, type compatibility, and how values can be used
  - A type judgment is an assertion that expression **x** has type t
    - Often requires the context of a type environment (i.e., symbol table)
  - “Strongly typed” if every expression can be assigned an unambiguous type
  - “Statically typed” if all types can be assigned at compile time
  - “Dynamically typed” if some types can only be discovered at runtime

- Benefits of a robust type system
  - Earlier error detection
  - Better documentation
  - Increased modularization

Formal Type Theory

- A formal type system is a set of type inference rules
  - Each rule has a name, zero or more premises (above the line), and a conclusion (below the line)
  - Premises and conclusions are type judgments (**A ⊢ x : t**)
  - "⊢" is a ternary operator connecting expressions with types
  - Omit type for statements ("**A ⊢ s**" means "s is well-typed in environment A")

$$\text{TDec}\ \dfrac{}{\vdash \texttt{DEC} : \textbf{int}} \qquad \text{TTrue}\ \dfrac{}{\vdash \texttt{true} : \textbf{bool}} \qquad \text{TLoc}\ \dfrac{\texttt{ID} : \tau \in \Gamma}{\Gamma \vdash \texttt{ID} : \tau}$$

$$\text{TAdd}\ \dfrac{\Gamma \vdash e_1 : \textbf{int} \qquad \Gamma \vdash e_2 : \textbf{int}}{\Gamma \vdash e_1\ \text{‘}\texttt{+}\text{‘}\ e_2 : \textbf{int}} \qquad \text{TAssign}\ \dfrac{\texttt{ID} : \tau \in \Gamma \qquad \Gamma \vdash e : \tau}{\Gamma \vdash \texttt{ID}\ \text{‘}\texttt{=}\text{‘}\ e\ \text{‘}\texttt{;}\text{‘}}$$

$$\text{TFuncCall}\ \dfrac{\texttt{ID} : (\tau_1, \tau_2, \ldots, \tau_n) \rightarrow \tau_r \in \Gamma \qquad \Gamma \vdash e_1 : \tau_1 \qquad \Gamma \vdash e_2 : \tau_2 \qquad \ldots \qquad \Gamma \vdash e_n : \tau_n}{\Gamma \vdash \texttt{ID}\ \text{‘}\texttt{(}\text{‘}\ e_1, e_2, \ldots, e_n\ \text{‘}\texttt{)}\text{‘} : \tau_r}$$

Formal Type Theory

- Type proofs consist of composing multiple type rules
  - Apply rule instances recursively to form proof trees
  - Type environments (e.g., symbol tables, marked in rules with ⊢ operator) provide type context information
  - Proof structure is based on the AST structure ("syntax-directed")
  - **Curry-Howard correspondence** ("proofs as programs")

$$\dfrac{x : \mathrm{int} \in A \qquad \dfrac{\dfrac{\mathrm{foo} : (\mathrm{int}) \rightarrow \mathrm{int} \in A \qquad \dfrac{y : \mathrm{int} \in A}{A \vdash y : \mathrm{int}}\;\text{TVar}}{A \vdash \mathrm{foo}(y) : \mathrm{int}}\;\text{TFuncCall} \qquad \dfrac{}{A \vdash 1 : \mathrm{int}}\;\text{TDec}}{A \vdash \mathrm{foo}(y) + 1 : \mathrm{int}}\;\text{TAdd}}{A \vdash x = \mathrm{foo}(y) + 1}\;\text{TAssign}$$

$A = \{\ \mathrm{foo} : \mathrm{int} \rightarrow \mathrm{int},\ x : \mathrm{int},\ y : \mathrm{int}\ \}$

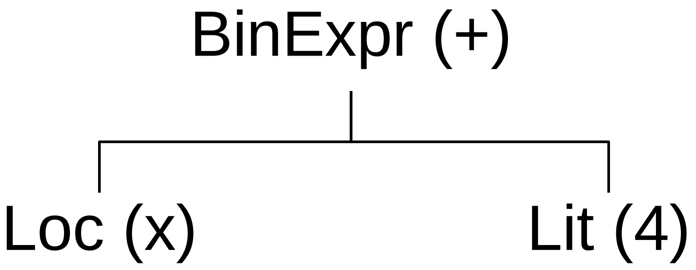
Formal Type Theory

- Is the following Decaf expression well-typed in the given environment?
  - If so, what is its type?

$$x + 4$$

$$A = \{ x : \text{int} \}$$

AST:


BinExpr (+)

Loc (x)

Lit (4)

Formal Type Theory

$$\text{TLoc}\ \frac{\texttt{ID} : \tau \in \Gamma}{\Gamma \vdash \texttt{ID} : \tau} \qquad\qquad \text{TDec}\ \frac{}{\vdash \texttt{DEC} : \textbf{int}}$$

$$\text{TAdd}\ \frac{\Gamma \vdash e_1 : \textbf{int} \qquad \Gamma \vdash e_2 : \textbf{int}}{\Gamma \vdash e_1 \text{ ‘+‘ } e_2 : \textbf{int}}$$

$$\dfrac{\text{TLoc}\ \dfrac{x : \text{int} \in A}{A \vdash x :} \qquad \dfrac{}{A \vdash 4 : \text{int}}\ \text{TDec}}{A \vdash x + 4 :}\ \text{TAdd}$$

$A = \{ x : \text{int} \}$

Formal Type Theory

$$\text{TLoc}\ \frac{\texttt{ID} : \tau \in \Gamma}{\Gamma \vdash \texttt{ID} : \tau} \qquad\qquad \text{TDec}\ \frac{}{\vdash \texttt{DEC} : \mathbf{int}}$$

$$\text{TAdd}\ \frac{\Gamma \vdash e_1 : \mathbf{int} \qquad \Gamma \vdash e_2 : \mathbf{int}}{\Gamma \vdash e_1 \text{ `}\mathbf{+}\text{` } e_2 : \mathbf{int}}$$

$$\frac{\text{TLoc}\ \dfrac{x : \text{int} \in A}{A \vdash x : \text{int}} \qquad \dfrac{}{A \vdash 4 : \text{int}}\ \text{TDec}}{A \vdash x + 4 : \text{int}}\ \text{TAdd}$$

$A = \{\ x : \text{int}\ \}$

P4: Static Analysis

- Language and project specifications provide rules to check at each type of AST node while traversing the AST
  - E.g., at ASTWhileLoop, make sure the conditional has a boolean type
  - E.g., at ASTBinaryExpr, if it’s an add make sure both operands are integers (or if it’s an equals make sure the operand types match)

$$\text{TDec}\,\frac{}{\vdash \texttt{DEC} : \textbf{int}} \qquad \text{THex}\,\frac{}{\vdash \texttt{HEX} : \textbf{int}} \qquad \text{TStr}\,\frac{}{\vdash \texttt{STR} : \textbf{str}}$$

$$\text{TTrue}\,\frac{}{\vdash \texttt{true} : \textbf{bool}} \qquad \text{TFalse}\,\frac{}{\vdash \texttt{false} : \textbf{bool}} \qquad \text{TSubExpr}\,\frac{\Gamma \vdash e : t}{\Gamma \vdash \text{‘(‘}\ e\ \text{‘)‘} : t}$$

$$\text{TAdd}\,\frac{\Gamma \vdash e_1 : \textbf{int} \qquad \Gamma \vdash e_2 : \textbf{int}}{\Gamma \vdash e_1\ \text{‘+‘}\ e_2 : \textbf{int}}$$

(similar for TSub (-), TMul (*), TDiv (/) and TMod (%))

$$\text{TEq}\,\frac{\Gamma \vdash e_1 : t \qquad \Gamma \vdash e_2 : t}{\Gamma \vdash e_1\ \text{‘==‘}\ e_2 : \textbf{bool}}$$

(similar for TNeq (!=))

$$\text{TWhile}\,\frac{\Gamma \vdash e : \textbf{bool} \qquad \Gamma \vdash b}{\Gamma \vdash \texttt{while}\ \text{‘(‘}\ e\ \text{‘)‘}\ b}$$

P4: Static Analysis

- General idea: traverse AST and reject invalid programs
  - Need to traverse the tree multiple times
    - Build symbol tables
    - Perform type checking
    - Later compiler passes
  - We could write the tree traversal code every time, but that would get tedious and would result in a lot of code duplication
    - Software engineering provides a better way in the form of the visitor design pattern

A brief digression ...

- What are "design patterns"?

(HINT: remember them from CS 345!)

A brief digression ...

- What are "design patterns"?
  - A reusable "template" or "pattern" that solves a common design problem
    - "Tried and true" solutions
  - Main reference: Design Patterns: Elements of Reusable Object-Oriented Software
    - "Gang of Four:" Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides

Common Design Patterns

- **Adapter** – Converts one interface into another
- **Factory** – Allows clients to create objects without specifying a concrete class
- **Flyweight** – Manages large numbers of similar objects efficiently via sharing
- **Iterator** – Provides sequential access to a collection
- **Monitor** – Ensures mutually-exclusive access to member variables
- **Null Object** – Prevents null pointer dereferences by providing "default" object
- **Observer** – Track and update multiple dependents automatically on events
- **Singleton** – Provides global access to a single instance object
- **Strategy** – Encapsulate interchangeable algorithms
- **Thread Pool** – Manages allocation of available resources to queued tasks
- **Visitor** – Provides an iterator over a (usually recursive) structure

Design Patterns

- Pros
  - Faster development
  - More robust code (if implemented properly)
  - More readable code (for those familiar with the patterns)
  - Improved maintainability
- Cons
  - Increased abstraction
  - Increased complexity
  - Philosophical: Suggests language deficiencies
    - Solution: Consider using a different language

Visitor Pattern

- Visitor design pattern: don't mix data and actions
  - Separates the **representation** of an object structure from the definition of **operations** on that structure
  - Keeps data class definitions cleaner
  - Allows the creation of new operations without modifying all data classes
  - Solves a general issue with OO languages
    - Lack of multiple dispatch (choosing a concrete method based on two objects' data types)
      - NOTE: This is stronger than parametric polymorphism alone
    - Less useful in functional languages with more robust pattern matching

General Form

- Data: Abstract**Element** (`ASTNode`)
  - ConcreteElement1 (`ASTProgram`)
  - ConcreteElement2 (`ASTVariable`)
  - ConcreteElement3 (`ASTFunction`)
  - etc.
  - All elements define "`Accept()`" method that recursively calls "`Accept()`" on any child nodes (this is the actual tree traversal code!)
- Actions: Abstract**Visitor** (`DefaultASTVisitor`)
  - ConcreteVisitor1 (`BuildParentLinks`)
  - ConcreteVisitor2 (`CalculateNodeDepths`)
  - ConcreteVisitor3 (`StaticAnalysis`)
    - `BuildSymbolTables`
    - `MyDecafAnalysis`
  - All visitors have "`VisitX()`" methods for each element type

Benefits

- Adding new operations is easy
  - Just create a new concrete visitor
  - In our compiler, create a new DefaultASTVisitor subclass
- No wasted space for state in data classes
  - Just maintain state in the visitors
  - In our compiler, we will make a few exceptions for state that is shared across many visitors (e.g., symbol tables)

Drawbacks

- Adding new data classes is hard
  - This won't matter for us, because our AST types are dictated by the grammar and won't change
- Breaks encapsulation for data members
  - Visitors often need access to all data members
  - This is ok for us, because our data objects are basically just structs anyway (all data is public)

Minor Modifications

- "`Accept()`" → "`traverse()`"
- "`Visit()`" → "`preVisit()`" and "`postVisit()`"
  - `preVisit()` allows preorder operations
  - `postVisit()` allows postorder operations
  - Also, a single inorder method: `inVisit(ASTBinaryExpr)`
- `DefaultASTVisitor` class
  - Implements `ASTVisitor` interface
  - Contains empty implementations of all "visit" methods
  - Allows subclasses to define only the relevant visit methods

Visitor example

```
public class WhileLoopCounter extends DefaultASTVisitor
{
    private int numWhileLoops = 0;

    @Override
    public void preVisit(ASTWhileLoop node)
    {
        numWhileLoops++;
    }

    @Override
    public void postVisit(ASTProgram node)
    {
        System.out.println("Number of while loops = " +
                numWhileLoops);
    }
}
```

In DecafCompiler.java:

```
ast.traverse(new WhileLoopCounter());
```

Decaf Project

- Project 3
  - `ASTVisitor`
  - `DefaultASTVisitor` (implements `ASTVisitor`)
    - `PrintDebugTree`
    - `ExportTreeDOT`
    - `BuildParentLinks` (activity)
    - `CalculateNodeDepths` (activity)
- Project 4
  - `PrintDebugSymbolTables` (extends `DefaultASTVisitor`)
  - `StaticAnalysis` (extends `DefaultASTVisitor`)
    - `BuildSymbolTables`
    - `DecafAnalysis` + **`MyDecafAnalysis`**
- Project 5
  - `ILOCGenerator` + **`MyILOCGenerator`**