Compiler Construction

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SoSe16

Lecture 6

Outline

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Structural recursion

Structural recursion is a form of recursion that goes along substructures of its input.

- Ex.: tree traversal, list processing
- Recursive functions over *algebraic data types* are often structurally recursive.
- If the recursive step does not refer to a subset of the initial argument, the recursion is called *generative*.
  - Ex. quicksort, which works on lists different from the input list

What is syntax-directed translation?

A translation is *syntax-directed* if it is a structural recursion over an (abstract) syntax tree.

- The major compilation phases can be implemented by syntax-directed translation:
  - NFA generation
  - Syntax analysis
  - Type checking
  - Code generation
- Other applications
  - Interpreter
  - Program transformation
  - Circuit design
  - ...

Syntax-directed translation is a very powerful technique!

Major implementation techniques

At implementation level, syntax-directed translation requires a tree traversal and a tree transformation. Different paradigms provide different support:

- In OOP, one may use the visitor pattern. The tree can simply be updated in-place.
- In FP, one uses pattern matching. For in-place updates, one employs a monadic style.

Outline

The Visitor pattern

The visitor pattern separates traversal of a composed structure from operations on its components. It includes two class hierarchies: for the visiting classes and for the visited classes.

- The visited classes contain a method `accept` that takes a visitor object.
  - `accept` is a callback function that passes itself back to its visitor. It is mere boilerplate code.
  - The client calls this method.
- The visitor class contains one `visit` function per substructure.
- A visitor framework provides two abstract base classes, for the visitor and the visited classes each.

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The expression grammar, again

Here is the expression grammar again:

```
EAdd. Exp  ::= Exp  "+" Exp1 ;
ESub. Exp  ::= Exp  "-" Exp1 ;
EMul. Exp1 ::= Exp1 "*" Exp2 ;
EDiv. Exp1 ::= Exp1 "/" Exp2 ;
EInt. Exp2 ::= Integer ;
```

- The expressions are the objects that are visited.
- The visitor contains one visit-method per BNFC label ("constructor").

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BNFC-generated framework

The abstract base classes depend only on the grammar.

BNFC generates the complete code for the abstract classes of the visitor automatically.

- For C++ , see `Absyn.[CH]`
- For Java, see `Absyn/Exp.java`

Generated base class for the visitor: C++

```
class Visitor {
public:
  virtual ~Visitor() {}
  virtual void visitExp(Exp *p) = 0;
  virtual void visitEAdd(EAdd *p) = 0;
  virtual void visitESub(ESub *p) = 0;
  virtual void visitEMul(EMul *p) = 0;
  virtual void visitEDiv(EDiv *p) = 0;
  virtual void visitEInt(EInt *p) = 0;

  virtual void visitInteger(Integer x) = 0;
  virtual void visitChar(Char x) = 0;
  virtual void visitDouble(Double x) = 0;
  virtual void visitString(String x) = 0;
  virtual void visitIdent(Ident x) = 0;
};
```

- There is one visit-method per label (plus BNFC built-in tokens).
- Note the C++ syntax for abstract methods.

Generated base class `Visitable` in C++

```
class Visitable {
public:
  virtual ~Visitable() {}
  virtual void accept(Visitor *v) = 0;
};
```

- The base class for the visited hierarchy does not even depend on the grammar but is always the same.
- Note the argument type of accept, `Visitor`.

Generated concrete visited classes

bnfc further generates all concrete classes of the visited hierarchy. Those classes depend on the particular grammar.

```
class Exp: public Visitable {...}

class EAdd: public Exp {...}
class ESub: public Exp {...}
class EDiv: public Exp {...}
class EMul: public Exp {...}
class EInt: public Exp {...}
```

- The start symbol, Exp, becomes the root class of the hierarchy: it inherits from Visitable.
- There is one class per BNFC label. Note the correspondence to the visiting methods.
- Its implementation is boilerplate code.

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Generated concrete visited classes (2)

```
class Exp: public Visitable {...}

class EAdd: public Exp {
    ...
    accept(Visitor *v) {
        v->visitEAdd(this);
    }
};
class ESub: public Exp {
    ...
    accept(Visitor *v) {
        v->visitESub(this);
    }
};
```

- Each visited class implements an `accept` method by calling the appropriate visitor method.
- The name of the visitor method is known (since it is also derived from the grammar).

Visitor pattern, so far

Thus far, we have seen three components of a visitor framework:

- The abstract classes `Visitor` and `Visitable`, and the concrete visited classes for the particular grammar (`Exp, EAdd`,..).

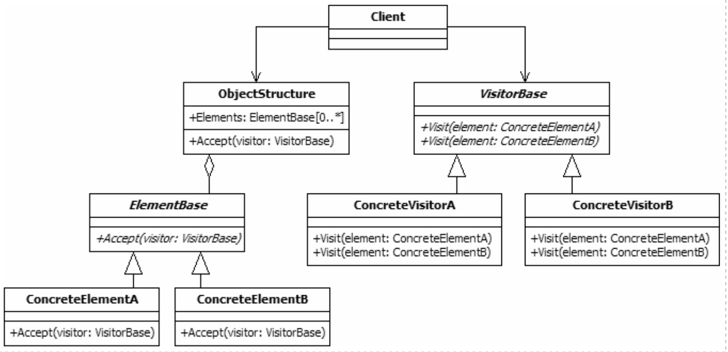
There are two more components: concrete *visitor* classes and a client.

- What is the purpose of traversing the AST?
  - Pretty-printing
  - Type checking
  - Evaluating
  - Translating
  - ...

  Each constitutes a *concrete* visitor of its own.
- The client is a small method or class that ties the two hierarchies.

The Visitor pattern: UML specification

http://www.blackwasp.co.uk/Visitor.aspx



In the previous example:

- In `bnfc`, `ElementBase` represents `Exp`, `ConcreteElementA` represents `EAdd`, `VisitorBase` represents `Visitor`.
- `Visitable` has no counterpart in the diagram.

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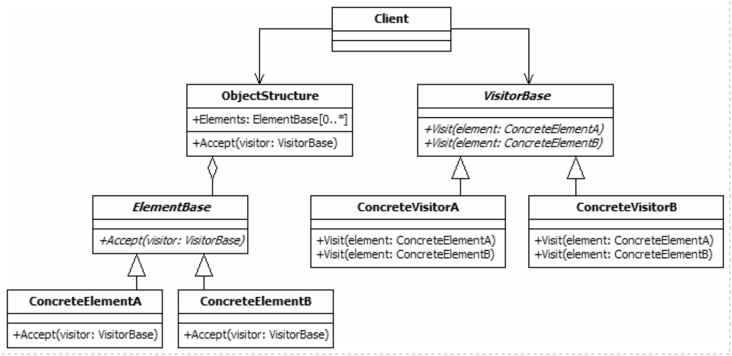
The Visitor pattern (cont'd)

http://www.blackwasp.co.uk/Visitor.aspx



Assume the client is an interpreter, with main function `eval`. Call sequence

- `eval` → `Accept` → `Visit` → `eval` → `Accept` → ... where the second eval is called on a substructure.

Call sequence (example, pseudo bnfc)

We did not look yet into the implementation of the interpreter (eval visitor), but a possible call sequence might look as follows:

$$
\begin{array}{ll}
 & \text{eval(EAdd(EInt(2),EInt(3)))} \\
\rightarrow & \text{EAdd(EInt(2),EInt(3)).Accept} \\
\rightarrow & \text{Visit(EAdd(EInt(2),EInt(3))} \\
\rightarrow & \text{eval(EInt(2))} + \text{eval(EInt(3))} \\
\rightarrow & \text{EInt(2).Accept} + \text{EInt(3).Accept} \\
\rightarrow & \text{Visit (EInt(2))} + \text{Visit(EInt(3))} \\
\rightarrow & 2 + 3
\end{array}
$$

Concrete visitor: skeleton interface

A concrete visitor still contains generated code: The names and signatures of the methods are known.

bnfc generates this code automatically.

```
#include "Absyn.H"

class Skeleton : public Visitor
{
public:
  void visitExp(Exp* p);
  void visitEAdd(EAdd* p);
  void visitESub(ESub* p);
  void visitEMul(EMul* p);
  void visitEDiv(EDiv* p);
  void visitEInt(EInt* p);

  ...
};
```

Concrete visitor: skeleton implementation

Even the implementation is partially known: The callback into the visited class can be generated automatically.

```
#include "Skeleton.H"

void Skeleton::visitEAdd(EAdd *eadd)
{
  /* Code For EAdd Goes Here */

  eadd->exp_1->accept(this);
  eadd->exp_2->accept(this);

}
```

- The visitor-specific code goes into the comments. Note: it might also be necessary to modify the generated invocation of `accept`.

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The visitor pattern in BNFC

- BNFC generates the complete code for the abstract classes of the visitor automatically. It further generates the abstract class `Visitable` and its concrete implementations.
  - For C++ , see `Absyn.H`
  - For Java, see `Absyn/Exp.java`
- For the concrete visitor classes it generates the boilerplate code
  - For C++ , see `Skeleton.[CH]`
  - For Java, see `VisitSkel.java`
- Manually, one only has to write the client and to complete the concrete visitor classes.

For Haskell, BNFC also generates a skeleton, but the boilerplate is very different (see below).

Writing your own visitor: work flow in C++

- Copy `Skeleton.[CH]` and rename.
- Add a client method that takes as parameter a `Visitable*`, add instance variable if needed.
- Edit the visit-methods.
- Copy `Test.C` to `Test2.C` and extend or modify it accordingly.
- Copy `Makefile` to `Makefile.new` and replace `Test.C` by `Test2.C` (and rename the main executable).
- Call `make -f Makefile.new`.

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Example (visitor)

An interpreter is easy to build as visitor:

1. Rename Skeleton.[CH] to Interpreter.[CH].
2. Add a client method that takes a Visitable* and calls accept on it. Since evaluation returns a value, we introduce an instance variable, val.

```
Integer Interpreter::eval(Visitable* v){
  v->accept(this);
  return val;
}
```

3. Edit the visit-methods. All accept and visit-methods return void. We therefore update val as a side effect:

```
void Interpreter::visitEAdd(EAdd *eadd)
{
  /* Code For EAdd Goes Here */
  // eadd->exp_1->accept(this);
  // eadd->exp_2->accept(this);
 val = eval(eadd->exp_1) + eval(eadd->exp_2);
}
```

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Example (visitor)

```
#include "Interpreter.H"

Interpreter::Interpreter() {}
Interpreter::~Interpreter() {}
Integer Interpreter::eval(Visitable* v){
  v->accept(this);
  return val;
}

void Interpreter::visitExp(Exp* t) {} //abstract class

void Interpreter::visitEAdd(EAdd *eadd)
{
  /* Code For EAdd Goes Here */
  // eadd->exp_1->accept(this);
  // eadd->exp_2->accept(this);
 val = eval(eadd->exp_1) + eval(eadd->exp_2);
}
void Interpreter::visitInteger(Integer x)
{
  /* Code for Integer Goes Here */
  val = x;
}
```

Building

```
> make -f Makefile
g++ -g -c Absyn.C
g++ -g -c Lexer.C
Calc.l:42:68: warning: control reaches end of non-void
function [-Wreturn-type]
int initialize_lexer(FILE *inp) { yyrestart(inp);
 BEGIN YYINITIAL; }
                                                                   ^←


1 warning generated.
g++ -g -c Parser.C
g++ -g -c Printer.C
g++ -g -c Test2.C
g++ -g -c Interpreter.C
Linking ...
g++ -g Absyn.o Lexer.o Parser.o Printer.o Interpreter.o Test2.o
    -o TestInterpreter
```

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Example (visitor)

```
> ./TestInterpreter input

Parse Successful!

[Abstract Syntax]
(EAdd (EInt 1) (EMul (EInt 3) (EInt 4)))

[Linearized Tree]
1+ 3* 4

[Value after Evaluation]
13
```

A visitor for type checking

Type checking can be realized by an appropriate visitor.

- The visited hierarchy is as before.
- The visitor, `TypeChecker`, follows the same logic as before.
- The biggest difference to the example before is not in the logic but in the data structures and types
  - The type checker relies on an environment: `Env`
  - The environment requires that its entries are encapsulated in types: `FunType`, ...

The class TypeChecker

```
class TypeChecker : public Visitor
{
public:
  ~TypeChecker();
  Type* typecheck(Visitable* v);
private:
  Type* ty_;

  class Env {
     ...
  };

  Env env_;
};

TypeChecker::~TypeChecker() {}
Type* TypeChecker::typecheck(Visitable* v) {
    v->accept(this);
    return ty_;
}
```

Example (type checking)

```
void TypeChecker::visitSInit(SInit *sinit)
{
  /* Code For SInit Goes Here */
  env_.updateVar(sinit->id_, sinit->type_); // id_, type_ ↩
      appropriate


}
void TypeChecker::visitId(Id x)
{
  /* Code for Id Goes Here */
  ty_ = env_.lookup(x);   // error handling omitted
}
```

- The environment is updated in initalization statements.
- It is looked up whenever an identifier is used.

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Syntax-directed type checking, part II

The alternative solution is based on pattern matching and a monadic style.

- Pattern matching is available in many functional languages.
  - Crucial ingredient: algebraic data types
  - Pattern matching on the constructors of an algebraic data type
- For *stateful* programming, functional languages employ special machinery: monads
  - IO monad, Err monad, State monad

What is an algebraic data type?

An *algebraic data types (ADT)* is a type that is defined as a *sum* type.

- Sum types are similar to union types, but each value can be only of one type (disjoint union of types).
- In OO-speak, “instanceOf” a value returns always the same type.
- Mathematical foundation in category theory

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Example (ADT)

In Haskell, the keyword data is used for the definition of an ADT, the |
operator is the sum operator.

```
data Value = VInt Integer | VDouble Double | VUndef
```

- The type `Value` has 3 constructors: `VInt`, `VDouble`, `VUndef`.
- Constructors can take arguments; the type of their arguments must be known.
- ADTs can be recursive types.

Example (ADTs and instances)

```
data Value = VInt Integer | VDouble Double | VUndef
> :type VInt 1
VInt 1 :: Value
> :type VUndef
VUndef :: Value
> :type VDouble 2
VDouble 2 :: Value
> VInt 1
VInt 1
> VDouble 2
VDouble 2.0
> VUndef
VUndef
```

- Values (instances) of type `Value` must be constructed using one of the three constructors.
- A constructor expression has a value. It cannot be further evaluated.

Another example (ADT)

- An ADT can be parameterized. In Haskell, type parameters are signified by lower-case characters.

```
data Err a = Ok a | Bad String      -- in the Haskell Prelude
> :type Ok (VInt 3)
Ok (VInt 3) :: Err Value
> :type Ok (VDouble 3)
Ok (VDouble 3) :: Err Value
> :type Ok (VUndef)
Ok (VUndef) :: Err Value
> :type Bad "ill-defined"
Bad "ill-defined" :: Err a
> Bad "ill-defined"
Bad "ill-defined"
```

- The type `Err` is parameterized by the expected type. It has two constructors: `Ok` takes a value of the expected type, `Bad` requires a string.
- `Err ()` is used when the Ok-value does not matter.

Example: the language Mini

```
-- Mini.cf

Prog. Program ::= [Stm] ;

terminator Stm "" ;

SDecl.  Stm ::= Type Ident ";"  ;
SAss.   Stm ::= Ident "=" Exp ";" ;
SBlock. Stm ::= "{" [Stm] "}" ;
SPrint. Stm ::= "print" Exp  ";" ;

EVar.    Exp1 ::= Ident ;
EInt.    Exp1 ::= Integer ;
EDouble. Exp1 ::= Double ;
EAdd.    Exp  ::= Exp "+" Exp1 ;

coercions Exp 1 ;

TInt.    Type ::= "int" ;
TDouble. Type ::= "double" ;
```

Implementing a grammar

We have already seen the ADTs for productions in BNFC:

```
data Program =
   Prog [Stm]
  deriving (Eq,Ord,Show,Read)
data Stm =
   SDecl Type Ident
  | SAss Ident Exp
  | SBlock [Stm]
  | SPrint Exp
  deriving (Eq,Ord,Show,Read)
data Exp =
   EVar Ident
  | EInt Integer
  | EDouble Double
  | EAdd Exp Exp
  deriving (Eq,Ord,Show,Read)
data Type =
   TInt
  | TDouble
  deriving (Eq,Ord,Show,Read)
```

ADTs and pattern matching

- ADTs suggest writing functions by pattern matching on the constructor.
- Ex.: statements are checked by pattern matching on the statement labels (constructors). (Recall that [Stm] refers to a list of statement.)

```
data Stm =
    SDecl Type Ident
  | SAss Ident Exp
  | SBlock [Stm]
  | SPrint Exp
   deriving (Eq,Ord,Show,Read)

checkStm env s =
      case s of
        SDecl t x        -> ...
        SAss x e         -> ...
        SBlock stms      -> ...
        SPrint e         -> ...
```

ADTs and pattern matching (2)

Similarly, expressions are checked/inferred/... by pattern matching on the expression labels.

```
data Exp =
   EVar Ident
 | EInt Integer
 | EDouble Double
 | EAdd Exp Exp
  deriving (Eq,Ord,Show,Read)

inferExp env e =
    case e of
      EVar x          -> ...
      EInt _          -> ...
      EDouble _       -> ....
      EAdd e1 e2      -> ...
```

Type checker: function types

http://www.cse.chalmers.se/edu/year/2011/course/TIN321/laborations/mini/haskell

```
module TypeChecker where

import AbsMini
import PrintMini
import ErrM

typecheck :: Program -> Err ()
checkStms :: Env -> [Stm] -> Err ()
checkStm  :: Env -> Stm -> Err Env
checkExp  :: Env -> Exp -> Type -> Err ()
inferExp  :: Env -> Exp -> Err Type
```

- The type checker module contains one function per syntactic category.
- The functions depend on the environment and return either an `Ok` value or a `Bad` message.
- The arrow notation is called *currying*. It is widely used in functional programming (see below for more).

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Pattern matching: checking statements

Statements are checked by pattern matching on the statement labels.

```
checkStm :: Env -> Stm -> Err Env
checkStm env s =
    case s of
      SDecl t x        -> addVar env x t
      SAss x e         -> do t <- lookupVar env x
                             checkExp env e t
                             return env
      SBlock stms      -> do checkStms (addScope env) stms
                             return env
      SPrint e         -> do inferExp env e
                             return env
```

- checkStm takes two arguments and pattern-matches on the second.
- Each of the four BNFC labels of Stm defines a case. The cases take different arguments.
- The logic is close to the typing rules.
- For the do/ return-notation, see below.

Pattern matching: infering expressions

Expression inference pattern-matches on the expression labels.

```
inferExp :: Env -> Exp -> Err Type
inferExp env e =
    case e of
      EVar x         -> lookupVar env x
      EInt _         -> return TInt
      EDouble _      -> return TDouble
      EAdd e1 e2
         -> do t1 <- inferExp env e1
               t2 <- inferExp env e2
               if t1 == t2
                 then return t1
                 else fail (printTree e1 ++ " has type " ++
                    printTree t1  ++ " but " ++ printTree e2
                    ++ " has type " ++ printTree t2)
```

- Each of the four syntactic categories constitute a case.
- Inference proceeds recursively. The base cases represent constants (EInt, EDouble, and variables). In Mini, operands of a binary expression must have the same type.

Record type

- A record is an algebraic data type with one constructor ("product type").
- In Haskell, records have a special syntax: `{..}` and symbolic names.
- Example:

```
data Env = Env {
     context ::  [[(Ident, Type)]]
}
```

  - The definition is equivalent to
    `data Env = Env [[(Ident, Type)]]`

- In the example, the record contains one field only. Typically, records are used to group several fields.

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Access functions for records

In Haskell, for every field name of a record, an access function is automatically generated.

```
data Env = Env {
    context :: [[(Ident, Type)]]
}

> :type context
context :: Env -> [[(Ident, Type)]]
```

The environment: initialization and extension

- The initial environment initializes all fields:

```
emptyEnv :: Env
emptyEnv = Env {
     context = [[]]
}
```

- The environment gets populated when declarations are processed and type checking commences.
- The extension can be organized in-place, using the `State` monad.

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Outline

`State` in Haskell

- For in-place updates, use the type `State`:

```
State s
```

  where `s` denotes the type of the state, in our case: `Env`.
- For our purposes, you get by with two functions:
  - `get`: returns the state
  - `modify (s -> s)`: updates the state (by applying its argument to the old state)
- For the driver, you need an additional function
  - `execState` takes the initial environment `emptyEnv`, runs the check, and returns the final environment.
- The `State` type is a monad. Monads are a special feature in Haskell to allow for computations with side effects ("actions").

Example modify

- Adding a pair (x,t) to the environment in-place:

```
addVar :: Ident -> Type -> State Env ()
addVar x t = do
  (scope:rest) <- gets context
  case lookup x scope of
    Nothing ->
       modify (\env -> env{ context=((x,t):scope):rest })
    Just _  ->
       fail ("Variable " ++ printTree x ++
             " already declared.")
```

- The instruction gets retrieves the current context.
- The pair (x,t) is cons'ed with the current scope of the scope stack the context access function returns.
- modify changes the context field of that particular instance of Env.

Another example: gets

- Since the environment is stateful, one must use gets to get it.

```
lookupVar :: Ident -> State Env Type
lookupVar x = do
    (scope:rest) <- gets context
    return $ look x (scope:rest)
 where
    look x []               = error $ "Unknown variable " ++
                                      printTree x ++ "."
    look x (scope:rest)  = case lookup x scope of
                             Nothing -> look x rest
                             Just t  -> t
```

- The do-notation is used in monads to sequence computations. The layout rule applies.
- The method return is defined in the type class Monad. It is used to "inject" a value in a monad. It has nothing to do with the return statement in C-like languages.

```
:type return
return :: Monad m => a -> m a
```

Copy vs. monad

```
-- stateful environment
inferExp :: Exp -> State Env Type
inferExp e =
    case e of
        EVar x        -> lookupVar x
        EInt _        -> return TInt
        EDouble _     -> return TDouble
        EAdd e1 e2    -> do t1 <- inferExp e1
                            t2 <- inferExp  e2
                            if t1 == t2
                              then return t1
                              else fail (printTree e1 ++ "...")
-- functional environment
inferExp :: Env -> Exp -> Err Type
inferExp env e =
   case e of
      EVar x          -> lookupVar env x
      EInt _          -> return TInt
      EDouble _       -> return TDouble
      EAdd e1 e2       -> do t1 <- inferExp env e1
                             t2 <- inferExp env e2
                             if t1 == t2
```

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Function types

- The monadic style has in impact on the function types of the type checker.
- If the environment is updated in-place, it needs no longer be passed around.

```
-- stateful environment
checkStms :: [Stm] -> State Env ()
checkStm  :: Stm -> State Env ()
checkExp  :: Exp -> Type -> State Env ()
inferExp  :: Exp -> State Env Type
-- functional environment
checkStms :: Env -> [Stm] -> Err ()
checkStm  :: Env -> Stm -> Err Env
checkExp  :: Env -> Exp -> Type -> Err ()
inferExp  :: Env -> Exp -> Err Type
```

Summary

- Implementation via visitor resp. pattern matching
- Visitor pattern: two hierarchies, accept/visit callback
- Pattern matching on constructors of ADTs
- Monadic style, the State monad

References

- IPL, Ch. 4.11, 4.12