Abstract Syntax Trees

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- Parse Tree, Concrete Syntax
- Abstract Syntax Tree, Abstract Syntax
- Syntactic Sugar
- Traversals

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Structured Data for Input/Output: Trees

AST Generators

Syntax Definition Formalism [8]

```
module Tiger-Expressions
imports Tiger-Lexicals Tiger-Literals
exports
  sorts Exp Var
  context-free syntax
    Id                          →  Var         {cons("Var")}
    Var                         →  LValue
    LValue "." Id               →  LValue      {cons("FieldVar")}
    LValue "[" Exp "]"          →  LValue      {cons("Subscript")}
    IntConst                    →  Exp         {cons("Int")}
    StrConst                    →  Exp         {cons("String")}
    "nil"                       →  Exp         {cons("NilExp")}
    LValue                      →  Exp
    Var "(" {Exp ","}* ")"      →  Exp         {cons("Call")}
    Id "=" Exp                  →  InitField   {cons("InitField")}
    TypeId "{" {InitField ","}* "}"     →  Exp   {cons("Record")}
    TypeId "[" {Exp ","}+ "]" "of" Exp  →  Exp   {cons("Array")}
```

Exchanging Trees

Abstract Syntax Notation number One

ASN.1 [3, 5]

- an international standard
- specify data used in communication protocols
- powerful and complex language
- describe accurately and efficiently communications between homogeneous or heterogeneous systems

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ASN.1

```
Example DEFINITIONS ::=
BEGIN
    AddressType ::= SEQUENCE {
        name              OCTET STRING,
        number            INTEGER,
        street            OCTET STRING,
        apartNumber       INTEGER OPTIONAL,
        postOffice        OCTET STRING,
        state             OCTET STRING,
        zipCode           INTEGER
    }
END
```

ASN.1

Tags to avoid problems similar to matching `a*a*`.

```
Example DEFINITIONS ::=
BEGIN
    Letter ::= SEQUENCE {
        opening         OCTET STRING,
        body            OCTET STRING,
        closing         OCTET STRING,
        receiverAddr    [0] AddressType OPTIONAL,
        senderAddr      [1] AddressType OPTIONAL
    }
END
```

ATerms

Grammar of ATerms

```
t  ::= bt                 -- basic term
     | bt { t }           -- annotated term
bt ::= C                  -- constant
     | C(t1,...,tn)       -- n-ary constructor
     | (t1,...,tn)        -- n-ary tuple
     | [t1,...,tn]        -- list
     | "ccc"              -- quoted string
     | int                -- integer
     | real               -- floating point number
     | blob               -- binary large object
```

C is a *constructor* name — an identifier or a quoted string [2].

Examples of ATerms

- **constants** `abc`
- **numerals** `42`
- **literals** `"asdf"`
- **lists** `[], [1, "abc" 2], [1, 2, [3, 4]]`
- **functions** `f("a"), g(1,[])`
- **annotations** `f("a") {"remark"}`

Other Frameworks

- SGML/XML
  - YAXX: YAcc eXtension to XML [11]
- CORBA
- JSON
- YAML
- S-expressions (sexps)

Simple Implementation of AST in C++

Simple Grammar

$$
\begin{aligned}
\langle \texttt{exp} \rangle \;&::=\; \langle \texttt{exp} \rangle \; (\texttt{'+'} \mid \texttt{'-'} \mid \texttt{'*'} \mid \texttt{'/'}) \; \langle \texttt{exp} \rangle \\
&\mid\;\; \langle \texttt{num} \rangle \,.
\end{aligned}
$$

Expressions: Exp

```
class Exp
{
protected:
  virtual ~Exp ();
};
```

Binary Expressions: Bin

```
class Bin : public Exp
{
public:
  Bin (char oper, Exp* lhs, Exp* rhs)
    : Exp (), oper_ (oper), lhs_ (lhs), rhs_ (rhs)
  {}

  virtual ~Bin ()
  { delete lhs_; delete rhs_; }

private:
  char oper_; Exp* lhs_; Exp* rhs_;
};
```

Numbers: Num

```
class Num : public Exp
{
public:
  Num (int val)
    : Exp (), val_ (val)
  {}

private:
  int val_;
};
```

Constructing an AST

```
int
main ()
{
  Exp* tree = new Bin ('+', new Num (42), new Num (51));
  delete tree;
}
```

How to process the AST?

Constructing an AST

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How to process the AST?

Traversals in Compilers

- pretty printer
- name analysis
- unique identifiers
- desugaring
- type checking
- non local (escaping) variables
- inlining
- high level optimizations
- translation to other intermediate representations
- etc.

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Tagging the Abstract Syntax Tree

Some traversals discover information that change the translation:

- an escaping variable must not be stored in a register
- the code for `a < b` depends on the types of `a` and `b`
- `a := print_int (51)` must not produce a real assignment

Annotate some AST nodes.

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Annotate some AST nodes.

Supporting the `operator<<`

Expressions: Exp

```
#include <iostream>

class Exp
{
protected:
  virtual ~Exp ();
};

std::ostream&
operator<< (std::ostream& o, const Exp& tree)
{
  return o << "Uh oh...";
}
```

Binary Expressions: Bin

```
class Bin : public Exp
{
public:
  Bin (char oper, Exp* lhs, Exp* rhs)
    : Exp (), oper_ (oper), lhs_ (lhs), rhs_ (rhs)
  {}
  virtual ~Bin () { delete lhs_; delete rhs_; }

  friend ostream& operator<< (ostream& o, const Bin& tree);

private:
  char oper_; Exp* lhs_; Exp* rhs_;
};

ostream&
operator<< (ostream& o, const Bin& tree)
{
  return o << '(' << *tree.lhs_
           << tree.oper_ << *tree.rhs_ << ')';
}
```

Numbers: Num

```
class Num : public Exp
{
public:
  Num (int val)
    : Exp (), val_ (val)
  {}

  friend
  ostream& operator<< (ostream& o, const Num& tree);

private:
  int val_;
};

ostream& operator<< (ostream& o, const Num& tree)
{
  return o << tree.val_;
}
```

Invoking and Printing

```
int
main ()
{
  Bin* bin = new Bin ('+', new Num (42), new Num (51));
  Exp* exp = bin;
  std::cout << "Exp: " << *exp << std::endl;
  std::cout << "Bin: " << *bin << std::endl;
  delete bin;
}
```

Using operator<<

```
% ./bin2
Exp: Uh oh...
Bin: (Uh oh...+Uh oh...)
```

- compile time selection (*static binding*) based on the containing/variable type.
- We need it at run time (*dynamic binding*) based on the contained/object type.
  - also called *inclusion polymorphism*
  - provided by `virtual` in C++

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  - also called *inclusion polymorphism*
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Expressions: Exp

```
#include <iostream>

class Exp
{
public:
  virtual std::ostream& print (std::ostream& o) const = 0;
};
```

Binary Expressions: Bin

```
class Bin : public Exp
{
public:
  Bin (char op, Exp* l, Exp* r)
    : Exp (), oper_ (op), lhs_ (l), rhs_ (r)
  {}

  virtual ~Bin () {
    delete lhs_; delete rhs_;
  }

  virtual std::ostream& print (std::ostream& o) const {
    o << '('; lhs_->print (o); o << oper_;
    rhs_->print (o); return o << ')';
  }

private:
  char oper_; Exp* lhs_; Exp* rhs_;
};
```

Numbers: Num

```
class Num : public Exp
{
public:
  Num (int val) : Exp (), val_ (val)
  {}

  virtual std::ostream&
  print (std::ostream& o) const
  {
    return o << val_;
  }

private:
  int val_;
};
```

Using this AST

```
std::ostream&
operator<< (std::ostream& o, const Exp& e)
{
  return e.print (o);
}

int
main ()
{
  Bin* bin = new Bin ('+', new Num (42), new Num (51));
  Exp* exp = bin;
  std::cout << "Exp: " << *exp << std::endl;
  std::cout << "Bin: " << *bin << std::endl;
  delete bin;
}
```

Discussion

It works...

```
% ./exp3
Exp: (42+51)
Bin: (42+51)
```

but Bin::print is obfuscated.

```
std::ostream&
Bin::print (std::ostream& o) const
{
  o << '(';
  lhs_->print (o);
  o << oper_;
  rhs_->print (o);
  o << ')';
  return o;
}
```

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It works. . .

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  o << oper_;
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  o << ')';
  return o;
}
```

Making operator<< Polymorphic

Just use the operator<< in print!

```
class Exp {
public:
  virtual std::ostream& print (std::ostream& o) const = 0;
};

std::ostream& operator<< (std::ostream& o, const Exp& e) {
  return e.print (o);
}

std::ostream& Bin::print (std::ostream& o) const {
  return o << '(' << *lhs_ << oper_ << *rhs_ << ')';
}
```

Cuter, but you cannot pass additional arguments to print.

Making operator<< Polymorphic

Just use the operator<< in print!

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class Exp {
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Cuter, but you cannot pass additional arguments to print.

Separate processing and dispatching

- In the previous code, `operator<<` processes and dispatches
- Additional operations will require processing and dispatching

Processing

- Keep it external
- Add new easily

Dispatching

- Keep it internal
- Once for all:
  Factor it!

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operator<< to process

```
std::ostream& operator<< (std::ostream& o, const Bin& e)
{
  return o << '(' << *e.lhs_ << oper_ << *e.rhs_ << ')';
}

std::ostream& operator<< (std::ostream& o, const Num& e)
{
  return o << e.val;
}

std::ostream& operator<< (std::ostream& o, const Exp& e)
{
  return e.print (o);
}
```

operator<< to process

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{
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}
```

print to dispatch

```
class Exp {
public:
  virtual std::ostream& print (std::ostream& o) const = 0;
};

class Bin {
public:
  virtual std::ostream& print (std::ostream& o) const {
    return o << *this;
  }
  ...
};

class Num {
public:
  virtual std::ostream& print (std::ostream& o) const {
    return o << *this;
  }
  ...
};
```

Separate processing and dispatching

- Now `operator<<` processes
- `print` dispatches
- Each processing requires its dispatching
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Multimethods

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- Polymorphism over any argument, not only just on the object:

```
ostream& operator<< (ostream& o, virtual const Exp& e);
ostream& operator<< (ostream& o, virtual const Bin& e);
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- This is called multimethods
- CLOS, Common Lisp Object System

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Multimethods in C++

- No multimethods in C++ 03 (nor 1x)
- Simulate via a *trampoline*

```
ostream& operator<< (ostream& o, const Exp& e)
{
  return e.print (o);
}
virtual ostream& Exp::print (ostream& o) = 0;
virtual ostream& Bin::print (ostream& o) { ... };
virtual ostream& Num::print (ostream& o) { ... };
```

- Ask the hierarchy to perform the dispatch
- Additional work on the hierarchy
- The concept is spread in several files
- Requires the ability to edit the hierarchy

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Multimethods

- Support for indentation: a new argument is needed.
- Similarly if we want to return a value.
- Introduce structures carried in the traversals.

```
struct stick_t
{
  std::ostream& ostr;
  int res;
  unsigned tab;
};
void traverse (stick_t& s, const Exp& e);
void traverse (stick_t& s, const Bin& e);
void traverse (stick_t& s, const Num& e);
```

- Better yet: make them objects.

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Visitors

Visitors

Visitors encapsulate the traversal data and algorithm.

```
class PrettyPrinter
{
public:
  void visitBin (const Bin& e) {
    ostr_ << '('; ...
  }
  void visitNum (const Num& e); {
    ostr_ << e.val_;
  }

private:
  ostream& ostr_;
  unsigned tab_;
};
```

Class Visitor

```
#include <iostream>

// Fwd.
class Exp;
class Bin;
class Num;

class Visitor
{
public:
  virtual void visitBin (const Bin& exp) = 0;
  virtual void visitNum (const Num& exp) = 0;
};
```

Classes Exp and Num

```
class Exp {
public:
  virtual void accept (Visitor& v) const = 0;
};


class Num : public Exp {
public:
  Num (int val)
    : Exp (), val_ (val)
  {}

  virtual void accept (Visitor& v) const {
    v.visitNum (*this);
  }

private:
  int val_;
};
```

Class Bin

```
class Bin : public Exp
{
public:
  Bin (char op, Exp* l, Exp* r)
    : Exp (), oper_ (op), lhs_ (l), rhs_ (r)
  {}

  virtual ~Bin () {
    delete lhs_; delete rhs_;
  }

  virtual void accept (Visitor& v) const {
    v.visitBin (*this);
  }

private:
  char oper_; Exp* lhs_; Exp* rhs_;
};
```

Class PrettyPrinter

```
class PrettyPrinter : public Visitor
{
public:
  PrettyPrinter (std::ostream& ostr)
    : ostr_ (ostr) {}

  virtual void visitBin (const Bin& e) {
    ostr_ << '('; e.lhs_->accept (*this);
    ostr_ << e.oper_; e.rhs_->accept (*this); ostr_ << ')';
  }

  virtual void visitNum (const Num& e) {
    ostr_ << e.val_;
  }

private:
  std::ostream& ostr_;
};
```

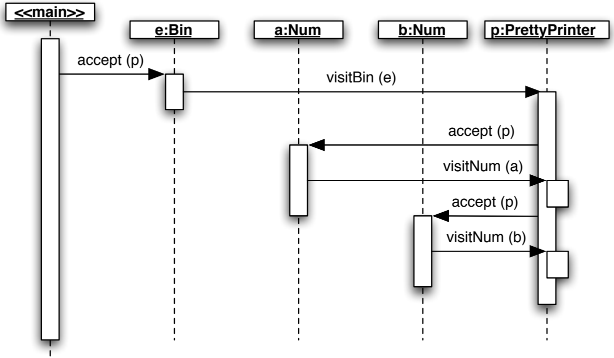
operator<< and main

```
std::ostream&
operator<< (std::ostream& o, const Exp& e)
{
  PrettyPrinter printer (o);
  e.accept (printer);
  return o;
}

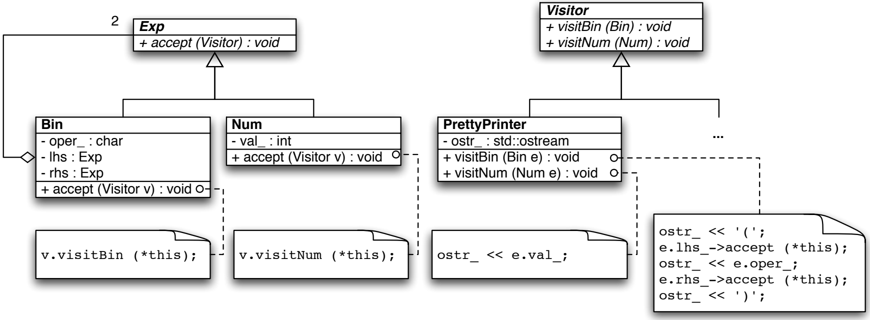
int
main ()
{
  Bin* bin = new Bin ('+', new Num (42), new Num (51));
  Exp* exp = bin;
  std::cout << "Bin: " << *bin << std::endl;
  std::cout << "Exp: " << *exp << std::endl;
  delete bin;
}
```

A pretty-printing sequence diagram

```
Exp* a = new Num (42); Exp* b = new Num (51);
Exp* e = new Bin ('+', a, b); std::cout << *e << std::endl;
```



A class diagram: Visitor and Composite design patterns



Further with Visitors

Visitors in C++

- `Visitor` and `ConstVisitor`
  similar to `iterator` and `const_iterator`
- Use C++ templates to factor
  (e.g., `Visitor` and `ConstVisitor`, see the lecture on generic programming)
- Use C++ overloading
  only `visit` instead of `visitBin` and `visitNum`

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Object Functions

- How about operator() instead of visit?
- But then, we can improve this

provided

- Derive from std::unary_function<Exp, void> to ease "functional programming" (#include <functional>)

Object Functions

- How about `operator()` instead of `visit`?
- But then, we can improve this

```
int eval (const Exp& e) {
  Evaluator eval;
  e.accept (eval);
  return eval.value;
}
```

```
int eval (const Exp& e) {
  Evaluator eval;
  eval (e);
  return eval.value;
}
```

provided

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```
void Evaluator::operator() (const Exp& e) {
  e.accept (*this);
}
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- Derive from `std::unary_function<Exp, void>` to ease "functional programming" (`#include <functional>`)

Sugaring Visitors 1

```
struct Evaluator : public ConstVisitor {
  virtual void operator() (const Exp& e) {
    e.accept (*this);
  }
  virtual void operator() (const Bin& e) {
    e.lhs_->accept (*this); int lhs = value;
    e.rhs_->accept (*this); int rhs = value;
    ... value = lhs + rhs; ...
  }
  virtual void operator() (const Num& e) {
    value = e.val;
  }
  int value;
};

int eval (const Exp& e) {
  Evaluator eval;
  eval (e);
  return eval.value;
}
```

Sugaring Visitors 2

```
struct Evaluator : public ConstVisitor
{
  ...
  virtual void
  operator() (const Bin& e) {
    ...
    value = eval (e.lhs_)
          + eval (e.rhs_);
    ...
  }

  virtual void
  operator() (const Num& e) {
    value = e.val;
  }

  int value;
};
```

One visitor per eval invocation

- A useless cost
- Easy automatic variables
- Harder for shared data (no `static` please!)

Sugaring Visitors 2

```
struct Evaluator : public ConstVisitor
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{
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  operator() (const Bin& e) {
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          + eval (e.rhs_);
    ...
  }

  virtual void
  operator() (const Num& e) {
    value = e.val;
  }

  int value;
};
```

One visitor per `eval` invocation

- A useless cost
- Easy automatic variables
- Harder for shared data (no `static` please!)

Sugaring Visitors 3

```
struct Evaluator : public ConstVisitor
{
  virtual int eval (const Exp& e) {
    e.accept (*this); return value;
  }

  virtual void operator() (const Exp& e) {
    e.accept (*this);
  }
  virtual void operator() (const Bin& e) {
    ...
    value = eval (e.lhs_) + eval (e.rhs_);
    ...
  }
  virtual void operator() (const Num& e) {
    value = e.val;
  }

  int value;
};
```

Sugaring the PrettyPrinter

```
virtual void
PrettyPrinter::operator() (const Bin& e)
{
  ostr_ << '(';
  e.lhs_->accept (*this);
  ostr_ << e.oper_;
  e.rhs_->accept (*this);
  ostr_ << ')';
}
```

- We could insert a `print` method
- But that's not nice
- We can use the `operator<<`
- But we no longer can pass additional arguments
- Unless...

Sugaring the PrettyPrinter

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- But that's not nice
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- But we no longer can pass additional arguments
- Unless... we can put data in the stream

Visitors Hierarchies

- Implement default behaviors (`DefaultVisitor`, `DefaultConstVisitor`)
- Overloaded virtual method must be imported.

```
class Renamer : public DefaultVisitor
{
public:
  typedef DefaultVisitor super_type;
  using super_type::operator();
  //...
}
```

Visitors Hierarchies

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class Renamer : public DefaultVisitor
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  //...
}
```

Visitors Hierarchies

- Specialize behaviors (`DesugarVisitor` < `Cloner`, `overload::TypeChecker` < `type::TypeChecker`, ...)

```
void TypeChecker::operator() (ast::LetExp& e)
{
  // The type of a LetExp is that of its body.
  super_type::operator() (e);
  type_default (e, type (e.body_get ()));
}
```

- Use C++ templates to factor (e.g., `DefaultVisitor` and `DefaultConstVisitor`)

Visitors Hierarchies

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}
```

- Use C++ templates to factor (e.g., `DefaultVisitor` and `DefaultConstVisitor`)

Visitor Combinators

- Work and traversal are still too heavily interrelated

→ Create visitors from basic traversal bricks: *combinators* [9].

Combinator	Description
Identity	Do nothing.
Sequence(v_1, v_2)	Sequentially run visitor v_1 then v_2.
Fail	Raise an exception.
Choice(v_1, v_2)	Try visitor v_1; if v_1 fails, try v_2.
All(v)	Apply visitor v sequentially to every immediate subtree.
One(v)	Apply visitor v sequentially to the immediate subtrees until it succeeds.

Visitor Combinators (cont.)

- Combine them to create visiting strategies.

$$
\begin{aligned}
\mathrm{Twice}(v) &\;=_{def}\; \mathrm{Sequence}(v, v) \\
\mathrm{Try}(v) &\;=_{def}\; \mathrm{Choice}(v, \mathit{Identity}) \\
\mathrm{TopDown}(v) &\;=_{def}\; \mathrm{Sequence}(v, \mathrm{All}(\mathrm{TopDown}(v))) \\
\mathrm{BottomUp}(v) &\;=_{def}\; \mathrm{Sequence}(\mathrm{All}(\mathrm{BottomUp}(v)), v)
\end{aligned}
$$

Desugaring

Syntactic Sugar in Lambda-Calculus

Curryfication

$$\lambda xy.e \Rightarrow \lambda x.(\lambda y.e)$$

Local variables

$$\text{let } x = e_1 \text{ in } e_2 \Rightarrow (\lambda x.e_2).e_1$$

Core Languages A sound basis.

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Core Languages A sound basis.

List Comprehension in Haskell

Quicksort in Haskell

```
qsort []     = []
qsort (x:xs) = qsort lt_x ++ [x] ++ qsort ge_x
                 where lt_x = [y | y <- xs, y <  x]
                       ge_x = [y | y <- xs, x <= y]
```

List Comprehension in Haskell

Sugared

```
[(x,y) | x <- [1 .. 6], y <- [1 .. x], x+y < 10]
```

Desugared

```
filter p (concat (map (\ x -> map (\ y -> (x,y))
       [1..x]) [1..6]))
    where p (x,y) = x+y < 10
```

List Comprehension in Haskell

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Desugaring

- Interferences with error messages, e.g., during type checking:

```
% echo '"true" | 42' | tc -T -
standard input:1.1-6: type mismatch
  condition type: string
  expected type: int
```

- The code the type-checker actually saw:

```
% echo '"true" | 42' | tc -XA -
/* == Abstract Syntax Tree. == */

function _main () =
  (
    (if "true"
      then 1
      else (42 <> 0));
    ()
  )
```

- Similarly with CPP

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Existing Tools

AST Generators

- built in generation of various hooks, including for visitors
- generation of visitor skeletons

Treecc [10]

The approach that we take with "treecc" is similar to that used by "yacc". A simple rule-based language is devised that is used to describe the intended behaviour declaratively. Embedded code is used to provide the specific implementation details. A translator then converts the input into source code that can be compiled in the usual fashion.

The translator is responsible for generating the tree building and walking code, and for checking that all relevant operations have been implemented on the node types. Functions are provided that make it easier to build and walk the tree data structures from within a "yacc" grammar and other parts of the compiler.

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Treecc: a simple example for expressions [4]

Yacc grammar

```
%token INT FLOAT

%%

expr: INT
    | FLOAT
    | '(' expr ')'
    | expr '+' expr
    | expr '-' expr
    | expr '*' expr
    | expr '/' expr
    | '-' expr
    ;
```

Treecc: a simple example for expressions (cont). [4]

Treecc description file

```
%node expression %abstract %typedef
%node binary expression %abstract = {
  expression* expr1;
  expression* expr2;
}
%node unary expression %abstract = {
  expression* expr;
}
%node intnum expression = {
  int num;
}
%node floatnum expression = {
  float num;
}
%node plus binary
%node minus binary
%node multiply binary
%node divide binary
%node negate unary
```

Treecc: a simple example for expressions [4]

Yacc grammar augmented to build the parse tree

```
%union {
    expression* node;
    int         inum;
    float       fnum;
}
%token INT FLOAT
%type <node> expr
%type <inum> INT
%type <fnum> FLOAT
%%
expr: INT               { $$ = intnum_create($1); }
    | FLOAT             { $$ = floatnum_create($1); }
    | '(' expr ')'      { $$ = $2; }
    | expr '+' expr     { $$ = plus_create($1, $3); }
    | expr '-' expr     { $$ = minus_create($1, $3); }
    | expr '*' expr     { $$ = multiply_create($1, $3); }
    | expr '/' expr     { $$ = divide_create($1, $3); }
    | '-' expr          { $$ = negate_create($2); }
    ;
```

The Introspector

Extract meta-data about programs (from compiler, build & make system, savannah/sourceforge management, packaging system, version control tools and mailing lists) and present it to you for making your job as a programmer easier.

The software is free software in the spirit of the GNU manifesto and is revolutionary in the freedoms that it intends on granting to its users.

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GCC-XML

C++ has become a popular and powerful language, but parsing it is a very challenging problem. This has discouraged the development of tools meant to work directly with the language.

There is one open-source C++ parser, the C++ front-end to GCC, which is currently able to deal with the language in its entirety. The purpose of the GCC-XML extension is to generate an XML description of a C++ program from GCC's internal representation.

Since XML is easy to parse, other development tools will be able to work with C++ programs without the burden of a complicated C++ parser. [7]

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The Case of the Tiger Compiler

Tiger Abstract Syntax

```
/Ast/                   (Location location)
  /Exp/                 ()
*   ArrayExp
*   AssignExp
*   BreakExp
*   CallExp
*     MethodCallExp
    CastExp             (Exp exp, Ty ty)
    ForExp              (VarDec vardec, Exp hi, Exp body)
*   IfExp
    IntExp              (int value)
*   LetExp
    NilExp              ()
*   ObjectExp
    OpExp               (Exp left, Oper oper, Exp right)
*   RecordExp
*   SeqExp
*   StringExp
    WhileExp            (Exp test, Exp body)
```

Tiger Abstract Syntax

```
/Ast/                (Location location)
  /Exp/              ()
*   /Var/
      CastVar        (Var var, Ty ty)
*     FieldVar
      SimpleVar      (Symbol name)
      SubscriptVar   (Var var, Exp index)

  /Dec/              (Symbol name)
    FunctionDec      (VarDecs formals, NameTy result, Exp body)
      MethodDec      ()
    TypeDec          (Ty ty)
    VarDec           (NameTy type_name, Exp init)

  /Ty/               ()
    ArrayTy          (NameTy base_type)
    ClassTy          (NameTy super, DecsList decs)
    NameTy           (Symbol name)
*   RecordTy
```

Tiger Abstract Syntax

```
DecsList        (decs_type decs)

Field           (Symbol name, NameTy type_name)

FieldInit       (Symbol name, Exp init)
```

Tiger Abstract Syntax

Some of these classes also inherits from other classes.

```
/Escapable/
  VarDec               (NameTy type_name, Exp init)

/Typable/
  /Dec/                (Symbol name)
  /Exp/                ()
  /Ty/                 ()

/TypeConstructor/
  /Ty/                 ()
  FunctionDec          (VarDecs formals, NameTy result, Exp body)
  TypeDec              (Ty ty)
```

Tiger Sugar

Light
- `if then`

Regular
- Unary -
- & and |
- Beware of (exp)
- Declarations (Types and Functions)

Extra
- `for`
- `?:` as in GNU C
- `where`
- Function overload

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Extra
- `for`
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Desugaring

Desugaring in Abstract Syntax

```
exp: exp "&" exp
{
  $$ = new IfExp (@$, $1,
                  new OpExp (@$,$3, OpExp::ne, new IntExp (@2, 0)),
                  new IntExp (@2, 0));
}
```

Desugaring in Concrete Syntax

```
exp: exp "&" exp
{
  $$ = parse::parse (parse::Tweast () <<
     "if " << $1 << " then " << $3 << "<> 0 else 0");
}
```

TWEAST: Text With Embedded Abstract Syntax Trees

Desugaring

Desugaring in Abstract Syntax

```
exp: exp "&" exp
{
  $$ = new IfExp (@$, $1,
                  new OpExp (@$,$3, OpExp::ne, new IntExp (@2, 0)),
                  new IntExp (@2, 0));
}
```

Desugaring in Concrete Syntax

```
exp: exp "&" exp
{
  $$ = parse::parse (parse::Tweast () <<
     "if " << $1 << " then " << $3 << "<> 0 else 0");
}
```

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Visitors

Stubs in AST nodes

'ast/let-exp.cc'

```
void LetExp::accept (ConstVisitor& v) const
{
  v (*this);
}

void LetExp::accept (Visitor& v)
{
  v (*this);
}
```

This can be factored by inheritance [1].

Inheritance to Factor (Mixin)

'parse/metavar-map.hh'

```
template <typename Data>
struct MetavarMap
{
  /// Append a metavariable.
  void append_ (int k,
                Data* d);
  /// Extract a metavariable.
  Data* take_  (int k);
  /// Metavariables.
  map<int, Data*> map_;
};
```

'parse/tweast.cc'

```
class Tweast
  : public MetavarMap<Exp>,
    public MetavarMap<Var>,
    public MetavarMap<NameTy>,
    public MetavarMap<DecsList>
{
  // ...
};
```

Inheritance to Factor (Mixin)

'parse/metavar-map.hh'

```
template <typename Data>
struct MetavarMap
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  /// Append a metavariable.
  void append_ (int k,
                Data* d);
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  Data* take_  (int k);
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  map<int, Data*> map_;
};
```

'parse/tweast.cc'

```
class Tweast
  : public MetavarMap<Exp>,
    public MetavarMap<Var>,
    public MetavarMap<NameTy>,
    public MetavarMap<DecsList>
{
  // ...
};
```

Visitors

PrettyPrinter Pretty-printer

Binder Bind uses to declarations

Renamer Unique names

TypeChecker Annotate nodes with their type

object::Binder Bind for Object Tiger

object::TypeChecker Check types for Object Tiger

overload::Binder Bind for overloaded Tiger

overload::TypeChecker Check types for overloaded Tiger

Visitors

- **PrettyPrinter** Pretty-printer
- **Binder** Bind uses to declarations
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object::DesugarVisitor Desugar Object Tiger code into the non-Object Tiger dialect ("Panther").

DesugarVisitor Handling syntactic sugar

BoundCheckingVisitor Bounds checking

Inliner Function inlining

Pruner Remove useless function definitions

EscapesVisitor Escaping variables

Translator Conversion to HIR

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