Computer Science 160
Translation of Programming Languages

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Context-Sensitive Analysis

Context-Sensitive Analysis

There is a level of correctness that is deeper than grammar

```
fie(a,b,c,d)
   int a, b, c, d;
{ … }

fee()
{
  int f[3], g[4], h, i,  j, k;
  char *p;
  call fie(h, i, "ab", j, k);
  k = f * i + j;
  h = g[17];
  printf("<%s,%s>.\n",p,q);
  p = 10;
}
```

What is wrong with this program?

- **declared g[4], used g[17]**
- **wrong number of args to fie()**
- **"ab" is not an int**
- **wrong dimension on use of f**
- **undeclared variable q**
- **10 is not a character string**

All of these are

"deeper than syntax"

Beyond Syntax

To generate code, the compiler needs to answer many questions

- Is “x” a scalar, an array, or a function? Is “x” declared?
- Are there names that are not declared? Declared but not used?
- Which declaration of “x” does each use reference?
- Is the expression “x * y + z” type-consistent?
- In “a[i,j,k]”, does a have three dimensions?
- Where can “z” be stored? *(register, local, global, heap, static)*
- How many arguments does “fie()” take?
- Does “*p” reference the result of a “malloc()” ?
- Do “p” and “q” refer to the same memory location?
- Is “x” defined before it is used?

These are beyond a CFG

Beyond Syntax

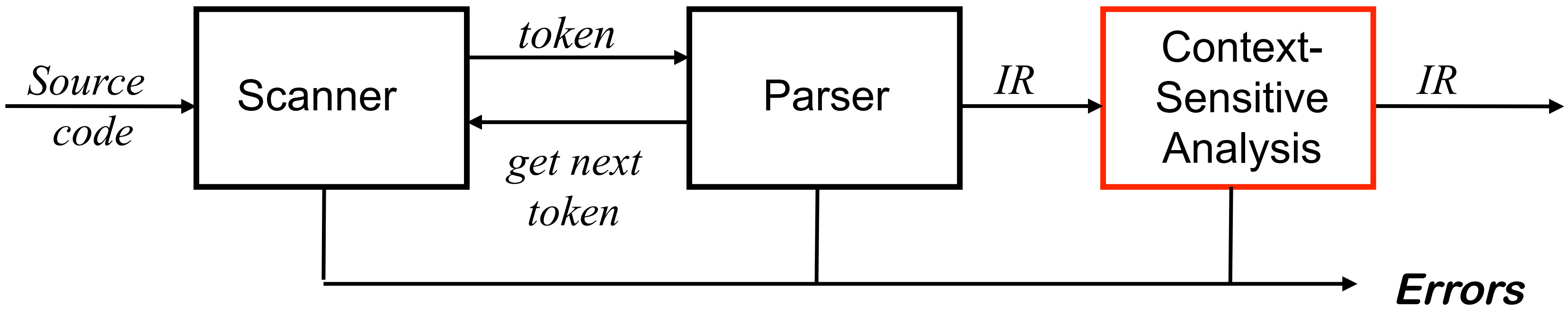
These questions are part of context-sensitive analysis

- Answers depend on values, not just tokens
  - answers depend on attributes of tokens
- Questions and answers involve non-local information
  - variable declarations, procedures
- Answers may involve computation

How can we answer these questions?

- Use formal methods
  - Context-sensitive grammars
  - Attribute grammars (semantic rules do not have side effects)
- Use ad-hoc techniques
  - Symbol tables
  - Ad-hoc code (use semantic rules that can have side effects)

Context-Sensitive Analysis



Context-Sensitive Analysis

- Properties we want to check involve non-local information
  - type-checking, variable declarations, procedure declarations
- Can be implemented as a traversal on the abstract syntax tree
- Can be integrated to parsing phase using ad-hoc translation schemes
- Formalisms such as attribute grammars can be used
- Ad-hoc techniques are more common than the formal techniques

Intermediate Representations: Overview

- There is more that one way to represent code as it is being generated, analyzed, and optimized.

high-level

Graphical IRs

- Abstract Syntax Trees (AST)
- Directed Acyclic Graphs (DAG)
- Control Flow Graphs (CFG)

Linear IRs

- Static Single Assignment Form (SSA)
- Stack Machine Code
- Three Address Code

low-level

Abstract Syntax Trees: Overview

- A compiler must do more than to recognize whether a sentence belongs to the language of a grammar in the form of syntax parse trees (in other words, generation of parse tree top-down or bottom-up for context-free grammars).

- Additionally, semantic actions of the parser productions check the types (building symbol tables), and later semantic analysis and intermediate code generation, optimization and target code generation are performed.

- The notion of abstract syntax is due to *John McCarthy*, 1963, who designed the abstract syntax for Lisp (no need to deal with all those parenthesis)

Abstract Syntax Trees: Overview

- The abstract syntax in the form of derivation (parse) trees separates syntax from semantics

- It might be possible to write an entire compiler that fits within the semantic action phrases of a Yacc / Bison parser (i.e., syntax-driven translation, e.g., like in a simple calculator interpreter). However, such a compiler is difficult to read and maintain and forces the compiler to analyze the program in exactly the order it is parsed

Difference between Parse Trees and ASTs

- To improve modularity, it is better to separate issues of syntax (parsing) from issues of semantics (type-checking and translation to target code).

- A parse tree is the dynamic data structure that later phases of the compiler can traverse: where each leaf corresponds to each token of the input, and one internal node corresponds for each grammar rule reduced during the parse. We may have a concrete and an abstract parse tree:

  – A *concrete parse tree* represents the concrete syntax of the source languages where many punctuation tokens are redundant, has extra non-terminal symbols and extra productions for factoring, elimination of left recursion, elimination of ambiguity

  – An *abstract parse tree* eliminates a lot of this redundant (but needed by the parser) information from concrete parse tree. An *abstract syntax* makes a clean interface between the parser and later phases of a compiler, and takes the form of the abstract parse tree.

Example: Abstract versus Concrete Syntax

- *Example*: Abstract syntax tree - the parser uses the concrete syntax to generate a simplified abstract tree corresponding to the ambiguous context free grammar (not good for a parser), but good enough for further phases of compilation.

Example concrete syntax

S	→	*Expr*
Expr	→	*Term Expr′*
Expr′	→	+ *Term Expr′*
	|	– *Term Expr′*
	|	ε
Term	→	*Factor Term′*
Term′	→	* *Factor Term′*
	|	/ *Factor Term′*
	|	ε
Factor	→	num
	|	id
	|	(*Expr*)

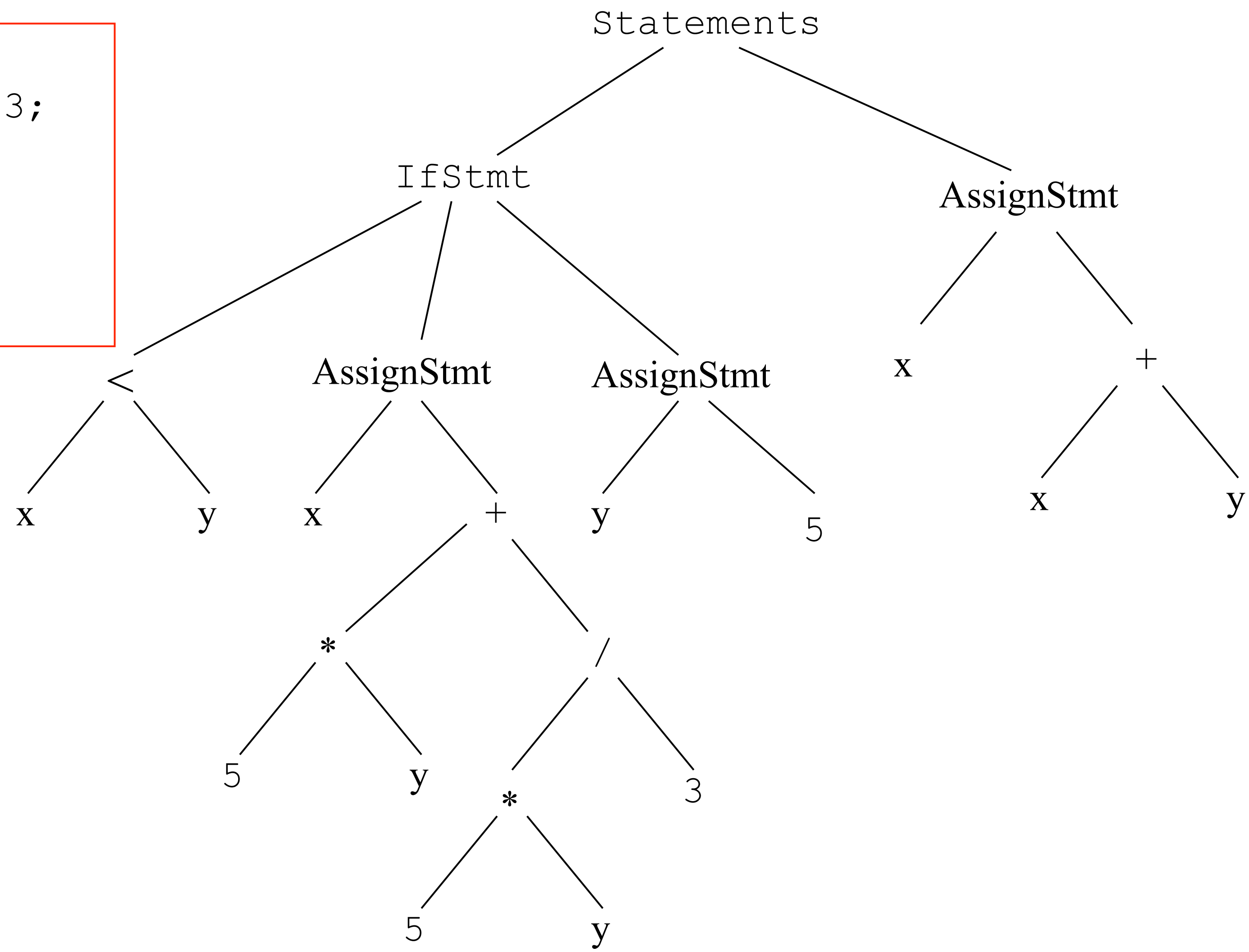
Example abstract syntax

S	→	*Expr*
Expr	→	*Expr* + *Expr*
	|	*Expr* – *Expr*
	|	*Expr* * *Expr*
	|	*Expr* / *Expr*
	|	id
	|	num

Much simpler, no punctuation is required, just enough to describe the structure of a program

Abstract Syntax Trees (ASTs)


```
if (x < y)
  x = 5*y + 5*y/3;
else
  y = 5;
x = x+y;
```



Object Oriented ASTs

- A tree is described by one or more abstract classes, corresponding to a symbol in the grammar
- Each abstract class is extended by one or more sub-classes, one for each grammar rule
- For each non-trivial symbol on the right hand side, there is a field in the corresponding class
- Each class has a constructor that initializes all fields and is thereafter immutable

```
# CDEF file for lang

Program ==> *Expr

Expr:Add ==> Expr Expr
Expr:Sub ==> Expr Expr
Expr:Div ==> Expr Expr
Expr:Mult ==> Expr Expr
Expr:Ident ==> SymName
Expr:Num ==> Primitive

# these classes should not be generated automagically
SymName external "symtab.hpp"
Primitive external "primitive.hpp"
```

Implementation (ast.hpp)


```
typedef Program* Program_ptr;
typedef Expr* Expr_ptr;

class Visitor
{
 public:
  virtual ~Visitor() {}
  virtual void visitProgramImpl(ProgramImpl *p) = 0;
  virtual void visitAdd(Add *p) = 0;
  virtual void visitSub(Sub *p) = 0;
  virtual void visitDiv(Div *p) = 0;
  virtual void visitMult(Mult *p) = 0;
  virtual void visitIdent(Ident *p) = 0;
  virtual void visitNum(Num *p) = 0;
  virtual void visitSymName(SymName *p) = 0;
  virtual void visitPrimitive(Primitive *p) = 0;
};

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

Implementation (ast.hpp)


```
class Program : public Visitable {
public:
   Attribute m_attribute;
   virtual Program *clone() const = 0;
};


// Program ==> *Expr
class ProgramImpl : public Program
{
  public:
  list<Expr_ptr> *m_expr_list;

  ProgramImpl(const ProgramImpl &);
  ProgramImpl &operator=(const ProgramImpl&);
  ProgramImpl(list<Expr_ptr> *p1);
  ~ProgramImpl();
  virtual void visit_children( Visitor* v );
  virtual void accept(Visitor *v);
  virtual  ProgramImpl  *clone() const;
  void swap(ProgramImpl &);
};
```

```
class Expr : public Visitable {
public:
   Attribute m_attribute;
   virtual Expr *clone() const = 0;
};

// Expr:Add ==> Expr Expr
class Add : public Expr
{
  public:
  Expr *m_expr_1;
  Expr *m_expr_2;

  Add(const Add &);
  Add &operator=(const Add &);
  Add(Expr *p1, Expr *p2);
  ~Add();
  virtual void visit_children( Visitor* v );
  virtual void accept(Visitor *v);
  virtual  Add  *clone() const;
  void swap(Add &);
};
```

Implementation (ast.cpp)


```
/********* Add ************/
 Add::Add(Expr *p1, Expr *p2)  {
          m_expr_1 = p1;
          m_expr_2 = p2;
          m_attribute.lineno = yylineno;
 }
 Add::Add(const Add & other) {
          m_expr_1 = other.m_expr_1->clone();
          m_expr_2 = other.m_expr_2->clone();
 }
 Add &Add::operator=(const Add & other) {
          Add tmp(other); swap(tmp); return *this; }
 void Add::swap(Add & other) {
          std::swap(m_expr_1, other.m_expr_1);
          std::swap(m_expr_2, other.m_expr_2);
 }
 Add::~Add() {
          delete(m_expr_1);
          delete(m_expr_2);
  }
 void Add::visit_children( Visitor* v ) {
          m_expr_1->accept( v );
          m_expr_2->accept( v );
  }
 void Add::accept(Visitor *v) { v->visitAdd(this); }
 Add *Add::clone() const { return new Add(*this); }
```

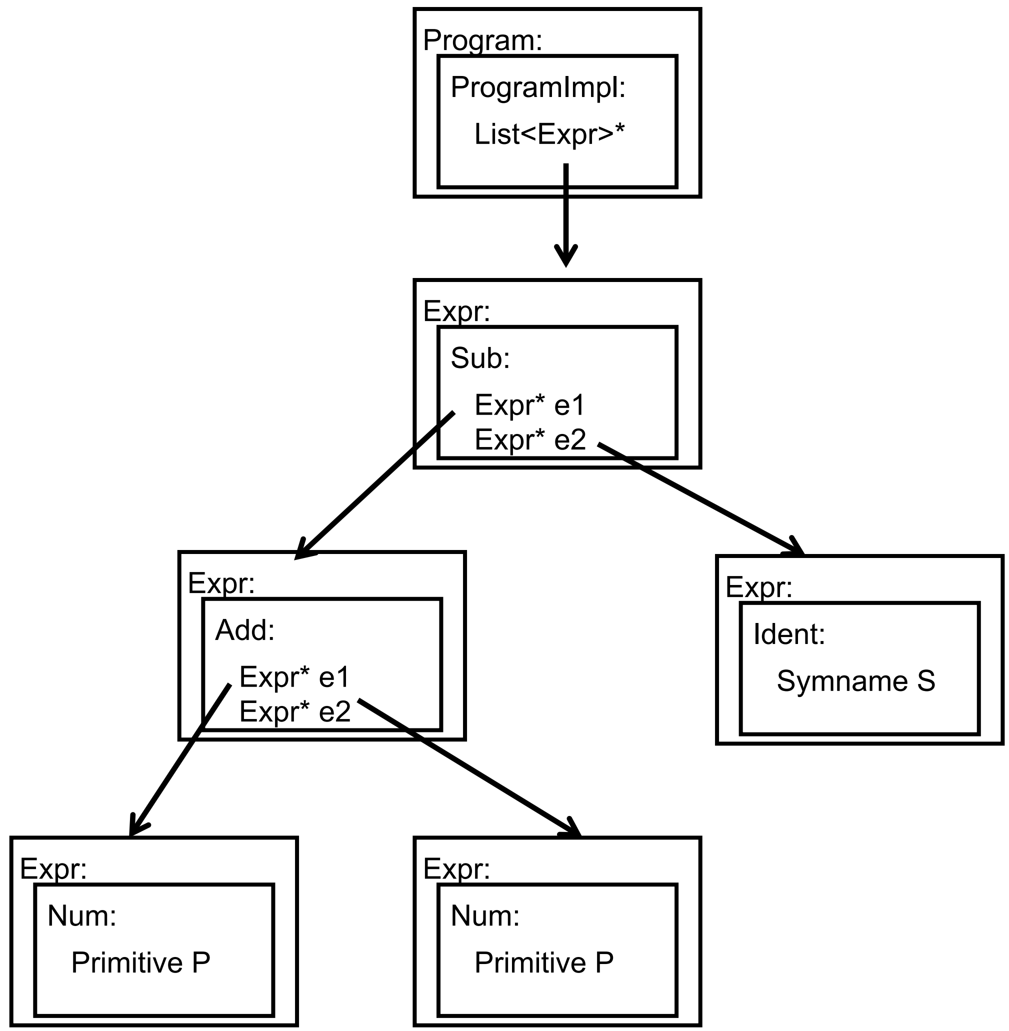
Implementation (ast.cpp)

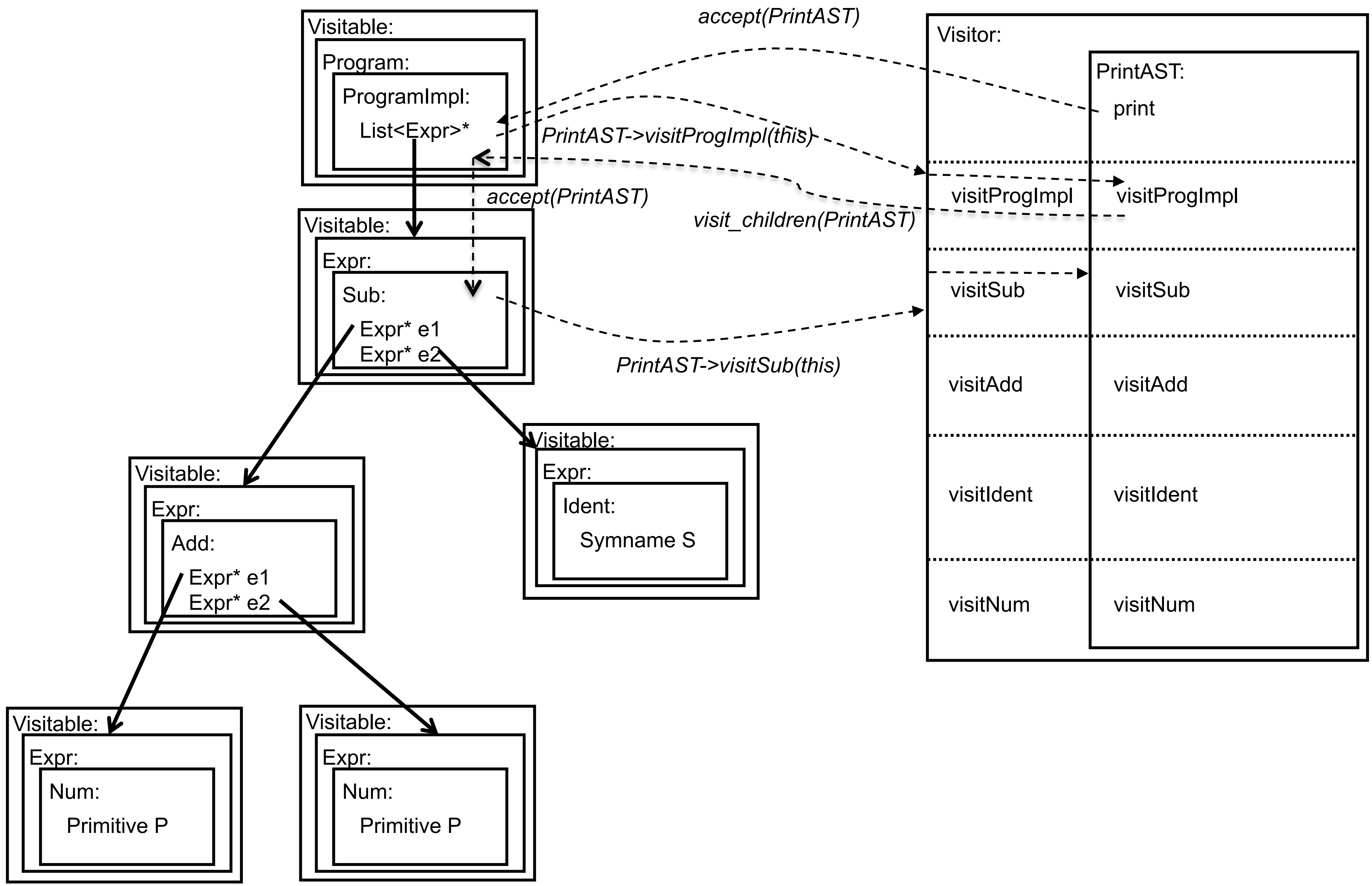

```
/********* ProgramImpl ************/
 ProgramImpl::ProgramImpl(list<Expr_ptr> *p1)  {
           m_expr_list = p1;
           m_attribute.lineno = yylineno;
 }
 ProgramImpl::ProgramImpl(const ProgramImpl & other) {
           m_expr_list = new list<Expr_ptr>;
           list<Expr_ptr>::iterator m_expr_list_iter;
           for(m_expr_list_iter = other.m_expr_list->begin();
             m_expr_list_iter != other.m_expr_list->end();
             ++m_expr_list_iter){
                      m_expr_list->push_back( (*m_expr_list_iter)->clone() );
           }
 }

 [... ]

void ProgramImpl::visit_children( Visitor* v ) {
           list<Expr_ptr>::iterator m_expr_list_iter;
           for(m_expr_list_iter = m_expr_list->begin();
             m_expr_list_iter != m_expr_list->end();
             ++m_expr_list_iter){
                      (*m_expr_list_iter)->accept( v );
           }
 }
 void ProgramImpl::accept(Visitor *v) { v->visitProgramImpl(this); }
```

Example: AST for 2+5-x




Visitable:
Program:
ProgramImpl:
List<Expr>*
accept(PrintAST)
PrintAST->visitProgImpl(this)
accept(PrintAST)
visit_children(PrintAST)
Visitable:
Expr:
Sub:
Expr* e1
Expr* e2
PrintAST->visitSub(this)
Visitable:
Expr:
Add:
Expr* e1
Expr* e2
Visitable:
Expr:
Ident:
Symname S
Visitable:
Expr:
Num:
Primitive P
Visitable:
Expr:
Num:
Primitive P
Visitor:
PrintAST:
print
visitProgImpl
visitProgImpl
visitSub
visitSub
visitAdd
visitAdd
visitIdent
visitIdent
visitNum
visitNum