Context-Sensitive Analysis
There is a level of correctness that is deeper than grammar

```c
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>.
", 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”
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

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

- **Graphical IRs**
  - Abstract Syntax Trees (AST)
  - Directed Acyclic Graphs (DAG)
  - Control Flow Graphs (CFG)
  - Static Single Assignment Form (SSA)

- **Linear IRs**
  - Stack Machine Code
  - Three Address Code

**high-level**

**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.
if \( x < y \)
\[
x = 5y + 5\frac{y}{3};
\]
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.

```plaintext
# 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"
```
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;
};
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)

```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); }
```
/********** 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

Program:
  ProgramImpl:
    List<Expr>*

  Expr:
    Sub:
      Expr* e1
      Expr* e2

  Expr:
    Add:
      Expr* e1
      Expr* e2

  Expr:
    Num:
      Primitive P

  Expr:
    Num:
      Primitive P

  Expr:
    Ident:
      Symname S
```
ProgramImpl:
  List<Expr>*

Expr:
  Sub:
    Expr* e1
    Expr* e2

Expr:
  Add:
    Expr* e1
    Expr* e2

Expr:
  Ident:
    Symname S

Expr:
  Num:
    Primitive P

Visitor:
  PrintAST:
    print
    visitProgImpl
    visitAdd
    visitIdent
    visitNum

Struct:
  Program:
    ProgramImpl:
      List<Expr>*

Struct:
  Expr:
    Sub:
      Expr* e1
      Expr* e2

Struct:
  Expr:
    Add:
      Expr* e1
      Expr* e2

Struct:
  Expr:
    Ident:
      Symname S

Struct:
  Expr:
    Num:
      Primitive P

Struct:
  Expr:
    Num:
      Primitive P

Visitor:
  VisitProgImpl:
    visitProgImpl

Visitor:
  VisitSub:
    visitSub

Visitor:
  VisitAdd:
    visitAdd

Visitor:
  VisitIdent:
    visitIdent

Visitor:
  VisitNum:
    visitNum
```