CS 412
Introduction to Compilers

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Lecture 12: More Static Semantics
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Static semantics

- Last time: introduced formal specification of type-checking rules: *static semantics*
- Concise form of static semantics: *inference rules/typing rules*
- Expression/statement/program is well-formed/well-typed/legal if
  - a *typing derivation* (proof tree) can be constructed using available inference rules
  - *syntax-directed* rules: no search required to construct proof, simple recursive checker works

Sequence

- Rule: A sequence of statements is well-typed if the first statement is well-typed, and the remaining are well-typed too too:

$$\frac{A \vdash S_1 : T_1 \qquad A \vdash (S_2\,;S_3\,;\,\ldots\,;S_n) : T_n}{A \vdash (S_1\,;S_2\,;\,\ldots\,;S_n) : T_n} \quad (block)$$

- What about variable declarations ?

Declarations

$$\frac{A \vdash id : T\,[\,= E\,] \quad : T_1 \qquad A,\, id : T \vdash (S_2\,;\,\ldots\,;S_n) : T_n}{A \vdash (id : T\,[\,= E\,];\, S_2\,;\,\ldots\,;S_n) : T_n} \quad (decl\ block)$$

= **unit** if no E

- This formally describes the type-checking code from two lectures ago!

Implementation

```
class Block { Stmt stmts[];
  Type typeCheck(SymTab s) { Type t;
    for (int i = 0; i < stmts.length; i++) {
      t = stmts[i].typeCheck(s);
      if (stmts[i] instanceof Decl)
         Decl d = (Decl)stmts[i];
         s = s.add(d.id, d.type.interpret());
    }
    return t;
  }
}
```

$$\frac{A \vdash S_1 : T_1 \qquad S_1 \text{ not a decl.} \qquad A \vdash (S_2\,;S_3;\ldots;S_n) : T_n}{A \vdash (S_1;\,S_2\,;\ldots;\,S_n) : T_n}$$

$$\frac{A \vdash id : T\,[\,= E\,] \quad : T \qquad A,\, id : T \vdash (S_2;\ldots;S_n) : T_n}{A \vdash (id : T\,[\,= E\,];\, S_2;\,\ldots;\,S_n) : T_n}$$

Function application

- If expression E is a function value, it has a type $T_1 \times T_2 \times \ldots \times T_n \rightarrow T_r$
- T_i are argument types; T_r is return type
- How to type-check $E(E_1,\ldots,E_n)$?

$$\frac{A \vdash E : T_1 \times T_2 \times \ldots \times T_n \rightarrow T_r \qquad A \vdash E_i : T_i \ \ (i \in 1..n)}{A \vdash E(E_1,\ldots,E_n) : T_r} \quad (fcn\ call)$$

Function-checking rule

- Iota function syntax

  $f\,(a_1 : T_1, \ldots, a_n : T_n) : T_r = E$

  (f an identifier)

- Type of E must match declared return type of function ($E : T$), but in what type context?

Add arguments to environment!

- Let A be the context surrounding the function declaration. Function decl

  $f\,(a_1 : T_1, \ldots, a_n : T_n) : T_r = E$

  is well-formed if

  $A,\, a_1 : T_1, \ldots,\ a_n : T_n \vdash\ E : T_r$

- Almost...what about recursion?

Example

```
fact(x: int) : int = {
    if (x==0) 1; else x * fact(x - 1); }
```

$$\dfrac{\dfrac{A2 \vdash x : int \quad A2 \vdash 0 : int}{A2 \vdash x{=}{=}0 : bool} \qquad A2 \vdash 1 : int \qquad \dfrac{A2 \vdash x : int \quad \dfrac{A2 \vdash fact : int \to int \quad \dfrac{A2 \vdash x : int \quad A2 \vdash 1 : int}{A2 \vdash x\text{-}1 : int}}{A2 \vdash fact(x - 1) : int}}{A2 \vdash x * fact(x - 1) : int}}{fact: int \to int,\ x : int \vdash \text{if } (x{=}{=}0) \ldots;\ \text{else} \ldots : int}$$

How to check return?

$$\dfrac{A \vdash E : T}{A \vdash \text{return } E : \textbf{unit}}\ (\textit{return1})$$

- A return statement produces no value for its containing context to use
- Also does not return control to containing context
- For now: type **unit**
- But... how to make sure the return type of the current function is T?

Put it in the symbol table

- Add entry {**return** : int } when we start checking the function, look up this entry when we hit a return statement.
- To check $f\,(a_1 : T_1, \ldots, a_n : T_n) : T_r = E$, in environment A, check

$$A,\, a_1 : T_1, \ldots,\ a_n : T_n,\ \textbf{return} : T_r\ \vdash\ E : T_r$$

$$\dfrac{A \vdash E : T \qquad \textbf{return} : T \in A}{A \vdash \text{return } E : \textbf{unit}}\ (\text{return})$$

Completing static semantics

- Rest of static semantics written in this style: read!
- Provides complete recipe for how to show a program type-safe
- Induction on size of expressions
  - have axioms for atoms: $\overline{A \vdash \text{true} : \textbf{bool}}$
  - for every AST node in language, have a rule showing how to prove it type-safe in terms of smaller exprs
- Therefore, have rules for checking all syntactically valid programs for type safety

& type checker always terminates!

Handling Recursion

- Java, Iota: all global identifiers visible throughout their module (even before defn.)
- Need to create environment (symbol table) containing all of them for checking each function definition
- Global identifiers bound to their types

  x: int ⇒ ..., x : int, ...
- Functions bound to function types

  gcd(x: int, y:int): int ⇒ ..., gcd: int × int → int, ...

Auxiliary environment info

- Entries representing functions are *not* normal environment entries

  { gcd: int × int → int }
- Functions not first-class values in Iota: can't use gcd as a variable name
- Need to flag symbol table entries
- Other entries (return, etc.) also must be flagged

Handling Recursion

```
f(x: int): int = g(x) + 1   g(x: int): int = f(x) - 1
```

- Need environment containing at least

  f: int → int, g: int → int

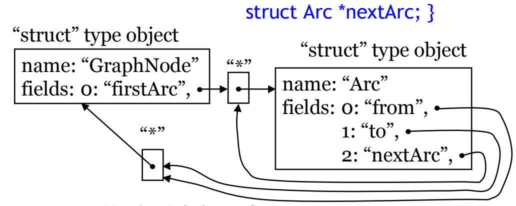
when checking both f and g
- Two-pass approach:
  - Scan top level of AST picking up all function signatures and creating an environment binding all global identifiers
  - Type-check each function individually using this global environment

Recursive Types

- Type declarations may be recursive too

Java: `class List { Object head; List tail; }`

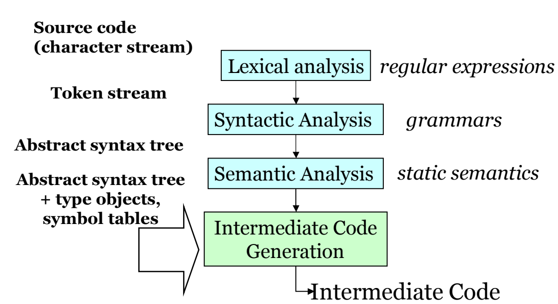
C:
```
struct GraphNode { struct Arc *firstArc; }
struct Arc { struct GraphNode *from, *to;
             struct Arc *nextArc; }
```



Interpreting type expressions

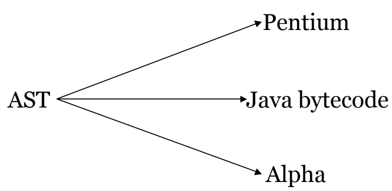
- How to convert recursive type expressions into cyclical graph structure?
- Solution: more semantic analysis passes
  - First pass: pick up all type names, create placeholder type objects and put into symbol table
  - Second pass: fill in type objects using symbol table to look up type names (can build global type context too)
  - Third pass: type-check actual code
- Mantra #2: add another pass

Where we are



Intermediate Code

- Abstract machine code - simpler
- Allows machine-independent code generation, optimization



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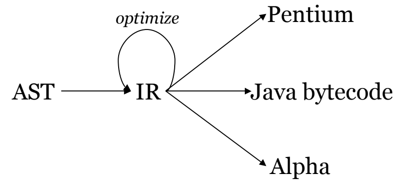
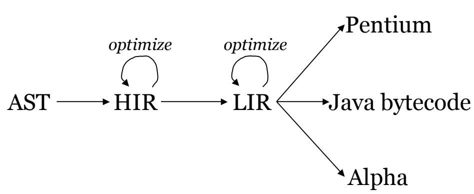


Optimizing compilers

- Goal: get program closer to machine code without losing information needed to do useful optimizations
- Need multiple IR stages



High-level IR (HIR)

- AST + new node types not generated by parser
- Preserves high-level language constructs
  - structured flow, variables, methods
- Allows high-level optimizations based on properties of source language (*e.g.* inlining, reuse of constant variables)
- Translation ideal for visitor impl.

Medium-level IR (MIR)

- Intermediate between AST and assembly
- Appel's IR: tree structured IR (triples)
- Unstructured jumps, registers, memory loc'ns
- Convenient for translation to high-quality machine code
- Other MIRs:
  - quadruples: a = b OP c ("a" is explicit, not arc)
  - UCODE: stack machine based (like Java bytecode)
  - advantage of tree IR: easy to generate, easier to do reasonable instruction selection
  - advantage of quadruples: easier optimization

Low-level IR (LIR)

- Assembly code + extra pseudo-instructions
- Translation to assembly code is trivial
- Allows optimization of code for low-level considerations: scheduling, memory layout

- Next time: an MIR