编译原理

5. 语义分析

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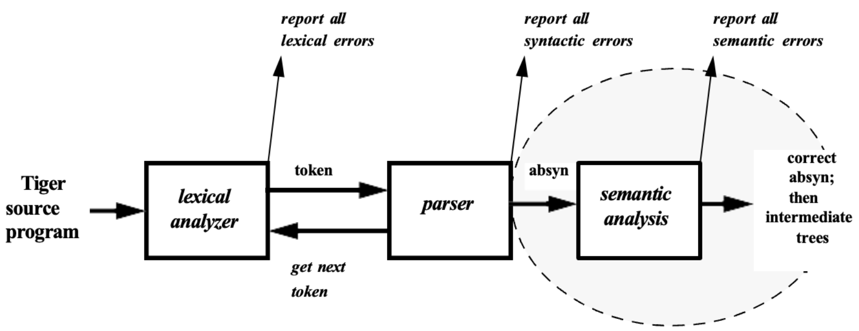
Content



report all
lexical errors
report all
syntactic errors
report all
semantic errors
Tiger
source
program
lexical
analyzer
token
get next
token
parser
absyn
semantic
analysis
correct
absyn;
then
intermediate
trees

The Limitations of CFG

- Consider the following grammar and programs
  - Does the corresponding parser accept the programs?

```
S ::= Decl  Stmt
Decl ::= Type  id | Decl; Decl
Type ::= string | int
Stmt ::= Stmt; Stmt |
         id = Exp | ...
Exp ::= Exp * Exp | id | num | char* | ...
```

string x; int z; x= "hello world"; z=x+1;	int x; int z; z=x+1;

- Many things can not be decided by syntax analysis
  - Does the dimension of a reference match the declaration?
  - Is an array access out of bound?
  - Where should a variable be stored (heap, stack,…)
  - …

(广义的)Semantic Analysis

- The reason of the limitations is that answering those questions depends on values instead of syntax

- We need to analyze the semantics of programs
  - Usually, this is done by traversing/analyzing various program representations
  - Examples of representations: AST, control flow graph (CFG), program dependence graph (PDG), value flow graph (VFG), SSA (single static assignment).

- Sample semantic analysis: type checking, code generation, dead code elimination, register allocation, etc

(狭义的)Semantic Analysis

- **编译原理相关课程默认的语义分析**
- **Determine some static properties of program via AST, e.g.,**
  - Scope and visibility of names
    - every variable is declared before use
  - Types of variables, functions, and expression
    - every expression has a proper type
    - function calls conform to definitions
  - …

```
ex.c:4:5: warning: assignment makes integer from pointer without a cast
ex.c:3:11: error: ‘i’ undeclared (first use in this function)
```

- **Translate the AST into some intermediate code**
  - Section 7 of Tiger book

Outline

1. Symbol Table
2. Symbols in the Tiger Compiler
3. Type Checking

1. Symbol Table

- **Symbol Table**
- **Efficient Implementation**

Symbol Table

- **Binding**: give a symbol a meaning, denotes by $\mapsto$
  - E.g.,

Name/Symbol	**Meaning/Attribute**
type identifier	type (e.g., int , string)
variable identifier	type, value, access info, …
function identifier	args.&reult type, …

- **Environment**: a set of bindings
  - E.g., an environment {g $\mapsto$ string, a $\mapsto$ int}
- Symbol table: the implementation of environment

Semantic analysis: traverse the abstract syntax tree (AST) in certain order while maintaining a symbol table

Motivating Example of Symbol Table

- Suppose at the very beginning the environment is σ_0

```
1. function f(a:int, b:int, c:int) =
2.     (print_int(a+c) ;
3.      let var j := a+b
4.          var a := "hello"
5.        in print(a); print_int(j)
6.      end;
7.      print_int(b)
8.     )
```

Line 1: $\sigma_1 = \sigma_0 + \{a \mapsto \text{int},\ b \mapsto \text{int},\ c \mapsto \text{int}\}$

Line 3: $\sigma_2 = \sigma_1 + \{j \mapsto \text{int}\}$

- In line2, the identifiers **a, c** can be looked up in σ_1
- In lines 3, the environment is updated

Motivating Example of Symbol Table

- Each local variable has a ***scope*** in which it is **visible**.

1.	`function f(a:int, b:int, c:int) =`	$\sigma_1=\sigma_0+\{a \mapsto int, b \mapsto int, c \mapsto int\}$
2.	`    (print_int(a+c) ;`	
3.	`     let var j := a+b`	$\sigma_2=\sigma_1+\{j \mapsto int\}$
4.	`         var a := "hello"`	$\sigma_3=\sigma_2+\{a \mapsto string\}$
5.	`       in print(a); print_int(j)`	
6.	`     end;`	
7.	`     print_int(b)`	
8.	`    )`	

- Let's consider line 4: $\sigma_3 = \sigma_2 + \{a \mapsto string\}$
  - σ2 contains a ↦ int. So, what is the binding of a in σ3?
  - 在σ3中，{a ↦ string}**覆盖**了σ_2 中a的binding!

约定: Bindings in the right-hand table override those in the left

Motivating Example of Symbol Table

- Each local variable has a ***scope*** in which it is **visible**.

1.	function f(a:int, b:int, c:int) =	$\sigma_1=\sigma_0+\{a \mapsto int, b \mapsto int, c \mapsto int\}$
2.	(print_int(a+c) ;	
3.	let var j := a+b	$\sigma_2=\sigma_1+\{j \mapsto int\}$
4.	var a := “hello”	$\sigma_3=\sigma_2+\{a \mapsto string\}$
5.	in print(a); print_int(j)	
6.	end;	σ_2, σ_3 都被“丢弃”
7.	print_int(b)	
8.	)	

- As the semantic analysis reaches **the end of each scope**, the identifier bindings local to that scope are discarded.
  - In line 6, $\boldsymbol{\sigma_3}$ is discarded and $\boldsymbol{\sigma_1}$ is back

小结: Symbol Table需实现的接口

- **insert**: 将名称绑定到相关信息(如类型), 如果名称已在符号表中定义，则新的绑定优先于旧的绑定

- **lookup**: 在符号表中查找名称，以找到名称绑定的信息

- **beginScope**: 进入一个新的作用域

- **endScope**: 退出作用域，将符号表恢复到进入之前的状态

Multiple Symbol Tables

- In some languages there can be several active environments at once: Each module, or class, or record in the program has a symbol table σ of its own.

```
package M;
class E {
    static int a = 5;
}
class N {
    static int b = 10;
    static int a = E.a + b;
 }
class D {
    static int d = E.a + N.a;
 }
```

Java

$\sigma 1 = \{ a \mapsto \textit{int} \}$

$\sigma 2 = \{ E \mapsto \sigma 1 \}$

$\sigma 3 = \{ b \mapsto \textit{int} , a \mapsto \textit{int} \}$

$\sigma 4 = \{ N \mapsto \sigma 3 \}$

$\sigma 5 = \{ d \mapsto \textit{int} \}$

$\sigma 6 = \{ D \mapsto \sigma 5 \}$

$\sigma 7 = \sigma 2 + \sigma 4 + \sigma 6$

In Java, forward reference is allowed. so *E*, *N*, and *D* are all compiled in the environment σ7. The result of the analysis is $\{M \mapsto \sigma 7\}$.

1. Symbol Table

- Symbol Table
- Efficient Implementation

Implementing Symbol Tables

$\sigma_2 = \sigma_1 + \{j \mapsto \text{int}\}$

- **Imperative Style**

  有了新的就看不到老的，但是退出scope时还能回得去

  – Modify σ1 until it becomes σ2

  – While σ2 exists, we cannot look things up in σ1

  – When we are done with σ2, we can undo the modification to get σ1 back again

- **Functional Style**

  每次发生变化的时候老的都保留着

  – Keep σ1 in pristine condition while creating σ2 and σ3

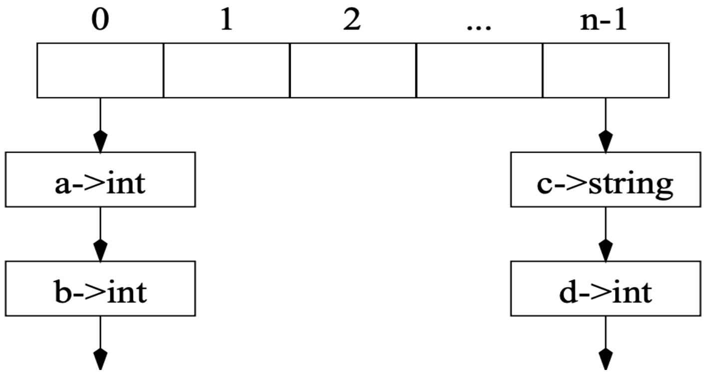
  – Easy to restore σ1

Either style can be used.

Problem Statement: Imperative Symbol Tables

- **Problem 1: How to support efficient lookup?**
  - **Solution:** Use hash table!
  - E.g., $\sigma' = \sigma + \{a \mapsto int\}$: insert <a, int> in the hash table

- **Problem 2: How to support deletion and revert to previous environment?**
  - **Solution**: Hash Table with external chaining
  - E.g., hash(a) -> <a, int> -> <a, string>



Efficient Imperative Symbol Tables

- **Hash Tables** - **an array of buckets**
- **Bucket** - **list of entries** (each entry maps identifier to binding)

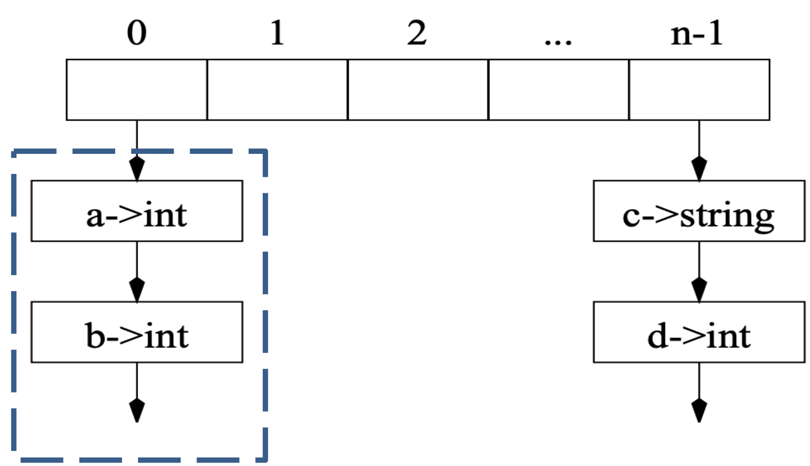
```
struct bucket { string key; void *binding;
struct bucket *next; };
#define SIZE 109

struct bucket *table[SIZE];

unsigned int hash(char *s0)
{ unsigned int h=0; char *s;
  for(s=s0; *s; s++)
    h=h*65599 + *s;
  return h;
}

struct bucket *Bucket (string key, void
*binding, struct bucket *next) {
  struct bucket *b=checked_malloc(sizeof(*b));
  b->key = key; b->binding = binding; b->next
= next;
  return b; }
```

$h = (\alpha^{n-1}c_1+\alpha^{n-2}c_2 +\ldots+ \alpha\, c_{n-1}+ c_n)$



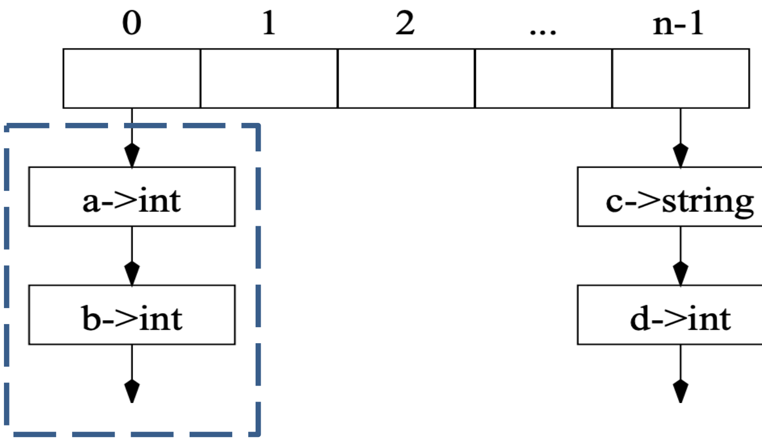
bucket

Efficient Imperative Symbol Tables

- Lookup entry for identifier *key* in symbol table:
  1. Apply *hash function* to `key` for getting array element `index`
  2. Traverse bucket in `table[index]` to find the binding.

     (table[*x*]: all entries whose keys hash to *x*)

```
void *lookup(string key) {
  int index=hash(key)%SIZE
  struct bucket *b;
  for (b = table[index]; b; b=b->next)
    if (0==strcmp(b->key,key))
      return b->binding;
  return NULL;
}
```

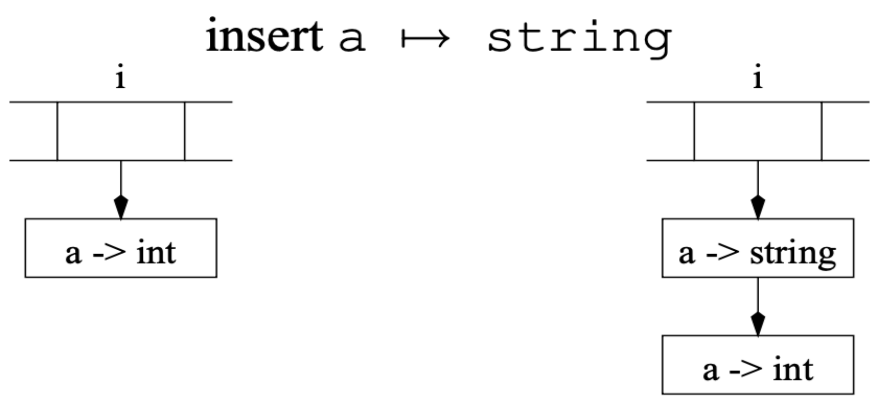


E.g., 假设想要查找标识符a的类型

1. 假定hash(c) = 0
2. 从table[0]的第一个元素开始逐一比较

Efficient Imperative Symbol Tables

- Insert new element at front of bucket
  - Consider $\sigma + \{a \mapsto \tau 2\}$ when σ contains $a \mapsto \tau 1$ already.
  - The insert function leaves $a \mapsto \tau 1$ in the bucket and puts $a \mapsto \tau 2$ earlier in the list: hash(a) -> <a, τ2 > -> <a, τ1>




```
void insert(string key, void *binding) {
  int index=hash(key)%SIZE;
  table[index]=Bucket(key, binding, table[index]);
}
```

Efficient Imperative Symbol Tables

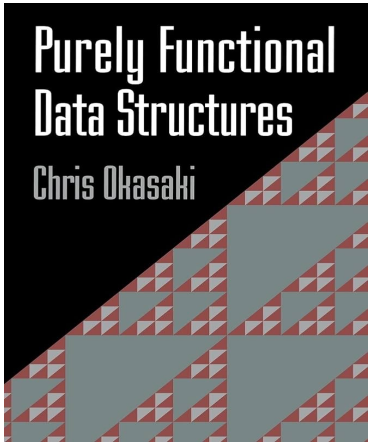
- Restore: pop items off items at front of bucket.
  - Consider $\sigma + \{a \mapsto \tau 2\}$ when σ contains $a \mapsto \tau 1$ already.
  - When pop(a) is done at the end of a's scope, σ is restored. (insertion and pop work in a stack-like fashion)
    - E.g., hash(a) -> <a, τ2 > -> <a, τ1> 变成 hash(a) -> <a, τ1>

```
void pop(string key) {
  int index=hash(key)%SIZE
  table[index]=table[index].next;
}
```

注: 为了处理不同scope, 还需其他辅助信息，比如指导“需要pop几次”(见第2部分 “Symbols in the Tiger Compiler”)

Efficient Functional Symbol Tables

- Basic idea the approach:
  - When implementing `σ2 = σ1 + {x ↦ t}`
  - Creating a **new** table `σ2`, instead of modifying `σ1`
  - When deleting, restore to the old table (方便快速"回退")
- 函数式编程中的"不可变数据结构"思想



https://en.wikipedia.org/wiki/Purely_functional_data_structure

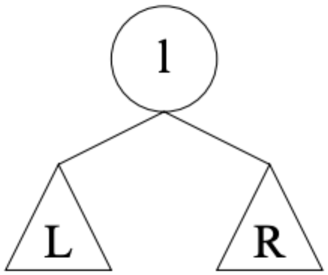
https://xavierleroy.org/CdF/2022-2023/1.pdf

Efficient Functional Symbol Tables

- Basic idea the approach:
  - When implementing **σ2 = σ1 + {x ↦ t}**
  - Creating a **new** table **σ2**, instead of modifying **σ1**
  - When deleting, restore to the old table

- 实现方式: binary search trees (BSTs).
  - Each node contains mapping from identifier (key) to binding.
  - Use string comparison for "less than" ordering.
  - For all nodes n ∈ L, key(n) < key(l)

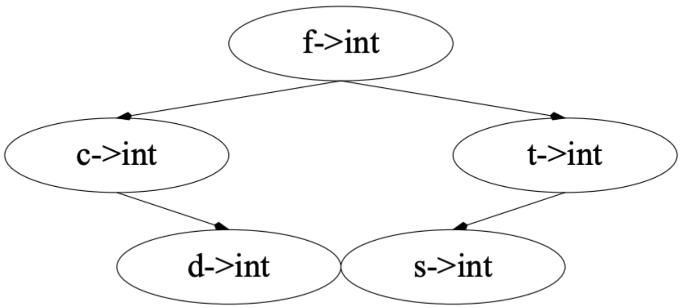
    For all nodes n ∈ R, key(n) > = key(l)



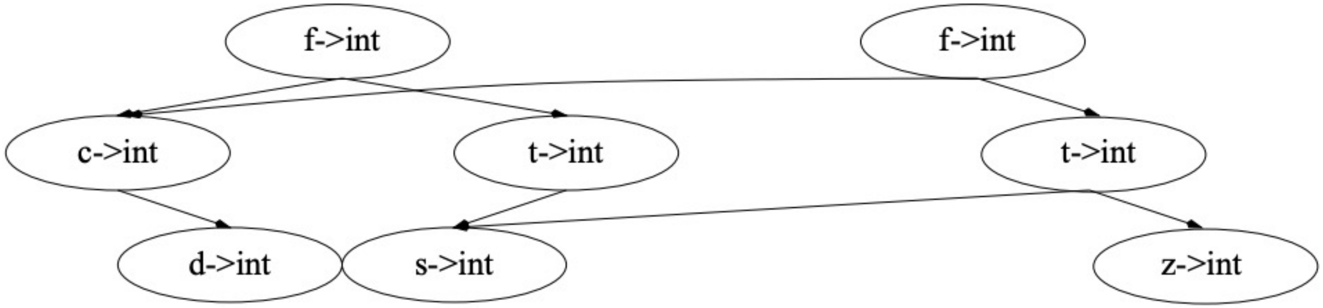
注: 用上述efficient impressive的方式也能实现，但是不够高效(见附录/虎书)

Efficient Functional Symbol Tables

- 实现方式: binary search trees (BSTs)
- **Lookup**： Olog(n) for a balanced tree of n nodes.



- **Insert:** Copy the nodes from the root to the parent of the inserted node
  - insert z → int, create node z, copy all ancestors of z



目的/效果: 避免完整拷贝所有旧版本

Summary: Implementation of Symbol Tables

- **Imperative Style : (side effects)**
  - When beginning-of-scope entered, entries added to table using side-effects. (old table destroyed)
  - When end-of-scope reached, auxiliary info used to remove previous additions. (old table reconstructed)
- **Functional Style : (no side effects)**
  - When beginning-of-scope entered, new environment created by adding to old one, but old table remains intact
  - When end-of-scope reached, retrieve old table.

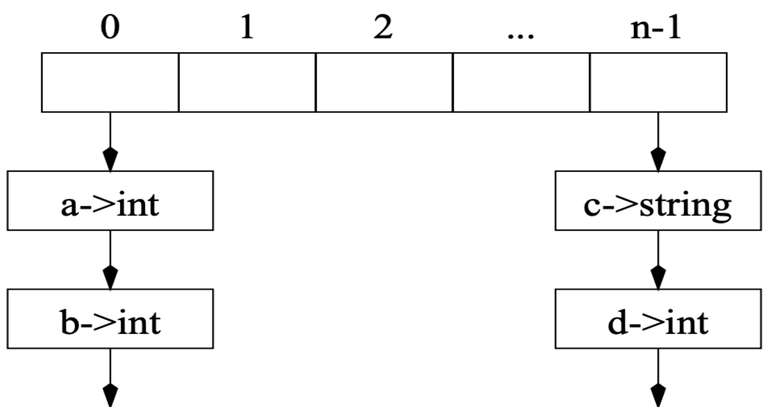
它们对lookup, insert, beginScope, endScope等接口的支持，复杂度上各有优势

2. Symbols in the Tiger Compiler

Issues With Table Implementations

- **Problem**: When key value = string, wee need expensive string comparisons when doing lookup operation.

```
void *lookup(string key) {
  int index=hash(key)%SIZE
  struct bucket *b;
  for (b = table[index]; b; b=b->next)
    if (0==strcmp(b->key,key))
      return b->binding;
  return NULL;
}
```



- **Solution**: use *symbol* data structure instead
  - Each symbol object associated with integer value
  - All occurrences of same string map onto same symbol (2 different strings map onto different symbols)
  - key value = symbol ⇒ do cheap integer comparisons during lookup

Symbols in The Tiger Compiler

The interface of symbols and symbol tables

- void *: We want different notions of binding for different purposes in the compiler – type bindings for types, value bindings for variables and functions

```
typedef struct S_symbol_ *S_symbol;
S_symbol S_symbol (string);
string S_name(S_symbol);

typedef struct TAB_table_ *S_table;
S_table S_empty( void);
void S_enter( S_table t,S_symbol sym, void *value);
void *S_look( S_table t, S_symbol sym);
void S_beginScope( S_table t);
void S_endScope( S_table t);
```

The Implementation of Symbols

```
static S_symbol mksymbol (string name , S_symbol next) {
  S_symbol s = checked_malloc(sizeof(*s));
  s->name = name; s->next = next;
  return s;
}

S_symbol S_symbol (string name) {
        int index = hash(name)%SIZE;
        S_symbol syms = hashtable[index], sym;
        for ( sym = syms; sym; sym = sym->next)
          if (0 == strcmp(sym->name, name)) return sym;
        sym = mksymbol(name,syms);
        hashtable[index] = sym;
   return sym;
}

string S_name (S_symbol sym) {
  return sym->name;
}
```

The Implementation of Symbol Tables

- The Tiger compiler in C uses destructive-update environments.
- An imperative table is implemented using a hash table.

```
// make a new S_Table
S_table S_empty(void) {
  return TAB_empty();
}
// insert a binding
void S_enter(S_table t, S_symbol sym, void
*value){
  TAB_enter(t,sym,value);
}
// look up a symbol
void *S_look(S_table t, S_symbol sym) {
  return TAB_look(t,sym);
}
```

The Implementation of Symbol Tables

For destructive-update environments:

- **S_beginScope**: Remembers the current state of the table
- **S_endScope**: Restores the table to where it was at the most recent beginScope that has not already been ended.

```
static struct S_symbol_ marksym = { “<mark>”, 0 };

void S_beginScope ( S_table t) {
  S_enter(t, &marksym, NULL);
}

void S_endScope( S_table t) {
  S_symbol s;
  do
    s= TAB_pop(t);
  while (s != &marksym);
}
```

The Implementation of Symbol Tables

Auxiliary stack:

- Showing in what order the symbols were “pushed” into the symbol table.
- As each symbol is popped, the head binding in its bucket is removed.
- **beginScope**: pushes a special marker onto the stack
- **endScope**: pops symbols off the stack until finds the topmost marker.

The Implementation of Symbol Tables

- The auxiliary stack can be integrated into the Binder by having a global variable top showing the most recent Symbol bound in the table.
- Pushing: copy top into the prevtop field of the Binder.

```
struct TAB_table_ {
  binder table[TABSIZE];
  void *top;
};


static binder Binder(void *key, void *value, binder next, void
*prevtop) {
  binder b = checked_malloc(sizeof(*b));
  b->key = key; b->value=value; b->next=next;
  b->prevtop = prevtop;
  return b;
}
```

3. Type Checking

- 类型及其作用
- Tiger类型系统
- Tiger类型检查

编程语言中的类型

- **变量的类型**
  - 限定了变量在程序执行期间的取值范围
- **类型化的语言(typed language)**
  - 变量都被给定类型的语言，如C/C++、Java、Go
  - 表达式、语句等程序构造的类型都可以静态确定
- **未类型化的语言(untyped language)**
  - 不限制变量值范围的语言, 如 LISP、JavaScript

no static types,
而非没有类型

类型在编程语言中的作用

- **开发效率：更高层次的编程抽象, e.g.,**
  - 多态、代数数据类型、依赖类型…
  - hoogle利用类型信息搜索API

编得快

- **运行性能：类型指导的编译优化, e.g.,**
  - 静态类型绑定避免运行时检查
  - 类型信息优化内存布局

跑得快

- **安全可靠：内存安全乃至功能正确, e.g.,**
  - Rust线性类型保障内存安全
  - LiquidHaskell精化类型保障功能正确

信得过

例: Refinement Type类型签名 add_two (x : int | x> 0) → x + 2

类型系统的形式化(不要求掌握)

- 类型系统是一种逻辑系统

有关自然数的逻辑系统

- 自然数表达式

  a+b, 3

- 良形公式

  a+b=3, (d=3) ∧ (c<10)

- 推理规则

$$\frac{a < b, \quad b < c}{a < c}$$

程序语言的类型系统

- 类型表达式

  int, int → int

- 定型断言(typing assertion)

  $x: \text{int} \mid\!- \ x+3 : \text{int}$

- 定型规则(typing rules)

$$\frac{\Gamma \mid\!- M : \text{int}, \ \Gamma \mid\!- N : \text{int}}{\Gamma \mid\!- M + N : \text{int}}$$

用推理规则来确定有哪些类型、
表达式的类型是什么

2. Type Checking

- 类型及其作用
- **Tiger类型系统**
- Tiger 类型检查

Key Problems in Type Checking

- **What are valid type expressions ?**
  - 总共有哪些类型，每个类型表达式对应到什么?
  - e.g., int, string, unit, nil, array of int, record ...
- **How to define two types are equivalent ?**
  - 比如，两个record类型是否相同?
- **What are the typing rules ?**
  - 要检查什么，比如形参和实参是否一致?

Tiger语言总共有哪些类型

- **The primitive type**: int, string
- **The constructed type**: using records and arrays from other types (primitive, record, or array)

typec → *type* *type-id* = *ty*

ty → *type-id*

→ '{' *tyfields* '}'

→ *array of* *type-id*

tyfields → ε

→ *id*: *type-id* {, *id*:*type-id*}

类型的文法定义

```
let type a = {x: int; y: int}
    type b = {x: int; y: int}
    var i : a := ...
    var j : b := ...
in i := j
end
```

类型声明案例

Tiger语言总共有哪些类型

- What are the binding of type identifiers and expresions:?

typec → *type* *type-id* = *ty*

ty → *type-id*

→ '{' *tyfields* '}'

→ *array of* *type-id*

tyfields → ε

→ *id: type-id {, id:type-id}*

```
typedef struct Ty_ty_ *Ty_ty;
struct Ty_ty_ {
  enum {Ty_record, Ty_nil, Ty_int, Ty_string,
        Ty_array, Ty_name, Ty_void} kind;
  union {
    Ty_fieldList record;
    Ty_ty array;
    struct {S_symbol sym; Ty_ty ty;} name;
  } u;
};
```

- When processing mutually recursive types: Ty_Name(sym, NULL)
    - a place-holder for the type-name sym

Tiger语言中的类型等价

- 注意: Every Tiger-language “record type expression” creates a new (and different) record type !

```
let type a = {x: int; y: int}
    type b = {x: int; y: int}
    var i : a := ...
    var j : b := ...
in i := j
end
```

It is illegal in Tiger.

```
let type a = {x: int; y: int}
    type b = a
    var i : a := ...
    var j : b := ...
in i := j
end
```

It is legal in Tiger.

类型等价Type Equivalence

- **Name equivalence (NE)** T1 and T2 are equivalent iff T1 and T2 are identical type names defined by the exact same **type declaration**.
- **Structure equivalence (SE)** T1 and T2 are equivalent iff T1 and T2 are composed of the same constructors applied in the same order.
  - **Tiger uses name equivalence.** E.g., `point` and `ptr` are equivalent under SE but not equivalent under NE

```
type point = {x : int, y : int}
type ptr = {x : int, y : int}
function f(a : point) = a
```

注: Type equivalence影响类型检查，如是否需要在Typing environment增加新的类型? 函数的形参和实参类型识别匹配?

Tiger语言的命名空间

- Tiger has two separate name spaces:
  - **Types**
  - **Functions** and **variables**

```
let type a = int
    var a := 1
in ...
end
```

Both a's can be used

```
let function a (b: int) = ...
    var a := 1
in ...
end
```

var a hides function a

3. Type Checking

- 类型及其作用
- Tiger类型系统
- Tiger 类型检查

Environments for Type Checking

```
let type a = int
    var a: a:= 5
    var b: a:= a
in b+a
end
```

- Tiger语义分析需要维护2个环境:
  1. **Type environment**

     Maps type symbol to type that it stands for Symbol -> Ty_ty
  2. **Value environment**
  - Maps variable symbol to its type symbol -> Ty_ty
  - Maps function symbol to parameter and result types

    symbol -> struct {Ty_tyList formals, Ty_ty result;}

Environments for Type Checking

```
typedef struct E_enventry_ *E_enventry;
struct E_enventry_ {
  enum {E_varEntry, E_funEntry} kind;
  union {
    struct {Ty_ty ty;} var;
    struct {Ty_tyList formals; Ty_ty result;} fun;
  } u;
};

E_enventry E_VarEntry(Ty_ty ty);
E_enventry E_FunEntry(Ty_tyList formals, Ty_ty result);

S_table E_base_tenv(void); /* Ty_ty environment */
S_table E_base_venv(void); /* E_enventry environment */
```

- Predefined type and value environments
  - Type environment "int" ↦ Ty_int, "string" ↦ Ty_string.
  - Value environment contains predefined functions of Tiger

Type-Checking for Tiger

- The Semant module (semant.h, semant.c) performs semantic analysis including type-checking – of abstract syntax

- Semantic analysis: four recursive functions over AST
  - 既做语义检查又做中间代码(IR Code)生成

```
Struct expty transVar (S_table venv, S_table tenv, A_var v);
Struct expty transExp (S_table venv, S_table tenv, A_exp a);
Void transDec (S_table venv, S_table tenv, A_dec d);
Ty_ty transTY (S_table tenv, A_ty a);
```

For now, not concerned with translation into IR code

Type-Checking for Tiger

1. **Type-checking expressions**
2. **Type-checking declarations**
   - Variable declarations
   - Type declarations
   - Function declarations
   - Recursive type declarations
   - Recursive function declarations

1. Type-Checking Expressions

```
Struct expty transVar (S_table venv, S_table tenv, A_var v);
Struct expty transExp (S_table venv, S_table tenv, A_exp a);
Void transDec (S_table venv, S_table tenv, A_dec d);
Ty_ty transTY (S_table tenv, A_ty a);
```

- **transExp :** Type-checking expressions: query && update the environments
- **Input** venv: value env., tenv: type env., a: expression

  Output: a translated expression and its Tiger-language type

```
struct expty {Tr_exp exp; Ty_ty ty;};
```

Example: Type-Checking e1 + e2

- Tiger's nonoverloaded type-checking for '+' expression
  - Suppose we we want to type-check e1 + e2
  - Both e1, e2 must be ints; Type of the expression is int

```
struct expty transExp(S_table venv, S_table tenv, A_exp a) {switch(a->kind)
{
   ...
   case A_opExp: {
     A_oper oper = a->u.op.oper;
     struct expty left =transExp(venv,tenv,a->u.op.left);
     struct expty right=transExp(venv,tenv,a->u.op.right);
     if (oper==A_plusOp) {
       if (left.ty->kind!=Ty_int)
         EM_error(a->u.op.left->pos, "integer required");
       if (right.ty->kind!=Ty_int)
         EM_error(a->u.op.right->pos,"integer required");
       return expTy(NULL,Ty_Int());
     }...
   }
 }
 assert(0); /* should have returned from some clause of the switch */
}
```

Rules for Type-Checking Expressions

- **Function call**: the types of formal parameters must be equivalent to the types of actual arguments.
- **If-expression** : **`if`** exp_1 **`then`** exp_2 **`else`** exp_3

  The type of exp_1 must be integer, the types of exp_2 and exp_3 should be equivalent.
- …

For more info, read **Appendix in Tiger Book.**

Type-Checking for Tiger

1. Type-checking expressions

2. **Type-checking declarations**
    - Variable declarations
    - Type declarations
    - Function declarations
    - Recursive type declarations
    - Recursive function declarations

2. Type-Checking Declarations

- **Declarations modify environments!**
- In Tiger, declarations appear only in a let expression.

```
struct expty transExp (S_table venv, S_table tenv, A_exp a)
{
  switch(a->kind) {
    ...
    case A_letExp: {
      struct expty exp;
      A_decList d;
      S_beginScope(venv); S_beginScope(tenv);
      for (d = a->u.let.decs; d; d=d->tail)
        transDec(venv,tenv,d->head);
      exp = transExp(venv,tenv,a->u.let.body);
      S_endScope(tenv); S_endScope(venv);
      return exp;
    }
  }...
}
```

- 变量声明、类型声明、函数声明
- let中声明的可以用在in里面

Variable Declarations

- Processing a variable declaration without a type constraint, e.g.,

var x := exp

```
void transDec(S_table venv, S_table tenv, A_dec d) {
  switch(d->kind) {
    case A_varDec: {
      struct expty e = transExp(venv,tenv,d->u.var.init);
      S_enter(venv, d->u.var.var, E_VarEntry(e.ty));
    }
  ...
  }
  ...
```

exp的类型ty(通过transExp获得)就是x的类型

Variable Declarations

- Processing a variable declaration with a type constraint:

  var x : type-id := exp

  - It will be necessary to check that the constraint and the initializing expression are compatible.
  - Also, initializing expressions of type Ty_Nil must be constrained by a Ty_Record type.

Type Declarations

- Nonrecursive type declarations

type type-id = ty

  - transTy: translates A_ty to Ty_ty recursively

直接利用抽象语法树(AST)节点上的类型信息(A_ty)

```
void transDec(S_table venv, S_table tenv, A_dec d) {
  ...
  case A_typeDec: {
    S_enter(tenv, d->u.type->head->name, transTy(d->u.type->head->ty));
  }
  ...
}
```

NOTICE: This program fragment only handles the type-declaration list of length 1!

Function Declarations

- Nonrecursive function declarations

function id (tyfields) : type-id = exp

```
void transDec(S_table venv, S_table tenv, A_dec d)
{
  switch(d->kind) {
    ...
    case A_functionDec: {
      A_fundec f = d->u.function->head;
      Ty_ty resultTy = S_look(tenv, f->result);
      Ty_tyList formalTys =
makeFormalTyList(tenv,f->params);
      S_enter(venv, f->name,
E_FunEntry(formalTys,resultTy));
      S_beginScope(venv);
      {A_fieldList l; Ty_tyList t;
       for(l=f->params, t=formalTys; l; l=l->tail,
t=t->tail)
         S_enter(venv,l->head->name,E_VarEntry(t-
>head));
      }
      transExp(venv, tenv, d->u.function->body);
      S_endScope(venv);
      break;
    }
    ...
```

```
function f(a:int):int = body
```

1. Look up ‘int’ in type env, ‘int’ $\rightarrowtail$Ty_int
2. venv’= venv + f $\rightarrowtail${ formals = Ty_int, result = Ty_int}
3. venv’’ = venv’ + a $\rightarrowtail$Ty_int
4. Type-check the body in {tenv, venv’’} using transExp
5. Return {tenv, venv’} for use in processing expressions which refer to f

NOTICE: The above code handles very restricted functions

Function Declarations

- The above code is very stripped-down implementation:
  - it handles only the case of a single function;
  - it handles only a function with a result
  - it doesn't handle program errors
  - it doesn't check that the type of the body expression matches the declared result type
  - …
- ***function f(a: ta, b: tb) : rt = body***
- ***makeFormalTyList***: traverses the list of formal parameters and returns a list of their types

Recursive Type Declarations

- How to convert the following declaration into the internal type representations ?

  type list = {first: int, rest: list}

- **Problem**: Processing type list = {first: int, rest: list} requires to lookup list from the type environment
  - *undefined type!*

- How to handle this problem?

Recursive Type Declarations

```
struct {
      S_symbol sym;
      Ty_ty ty;}
```

type list = {first: int, rest: list}

- **Solution: use two passes**
  - **1.** Put all the "headers" in the environment first (though they do not have bodies)
    - What is a header in this example? **type list =**
    - Use the special "name" type for the header
  - 2. Call transTy on the "body" of the type declaration
    - That is, the record type expression **{first: int, rest: list}**
    - The type that transTy returns can then be assigned into the ty field within the Ty_Name struct.

Recursive Type Declarations

- Every cycle in a set of mutually recursive type declarations **MUST** pass through a record or array declaration！
  - Tiger语言的重要特性之一

Tiger
```
type a = b
type b = a
```

It is illegal in Tiger.

Tiger
```
type a = b
type b = {i: a}
```

Tiger
```
type a = b
type b = d
type c = a
type d = a
```

It is illegal in Tiger.

contains an illegal cycle:
a -> b -> d -> a

Otherwise, the type checker will not terminate!

Recursive Function Declarations

- **Mutually recursive functions** handled similarly

  f call g, g call f

- **Problem**: P when we process the right hand side of function declarations, we may encounter symbols that are not defined in the env yet
- **Solution**
  - First pass: gathers information about the *header* of each function but leaves the bodies of the functions untouched.
  - Second pass: processes the bodies of all functions with the augmented environment.

Thank you all for your attention

Efficient Functional Symbol Tables

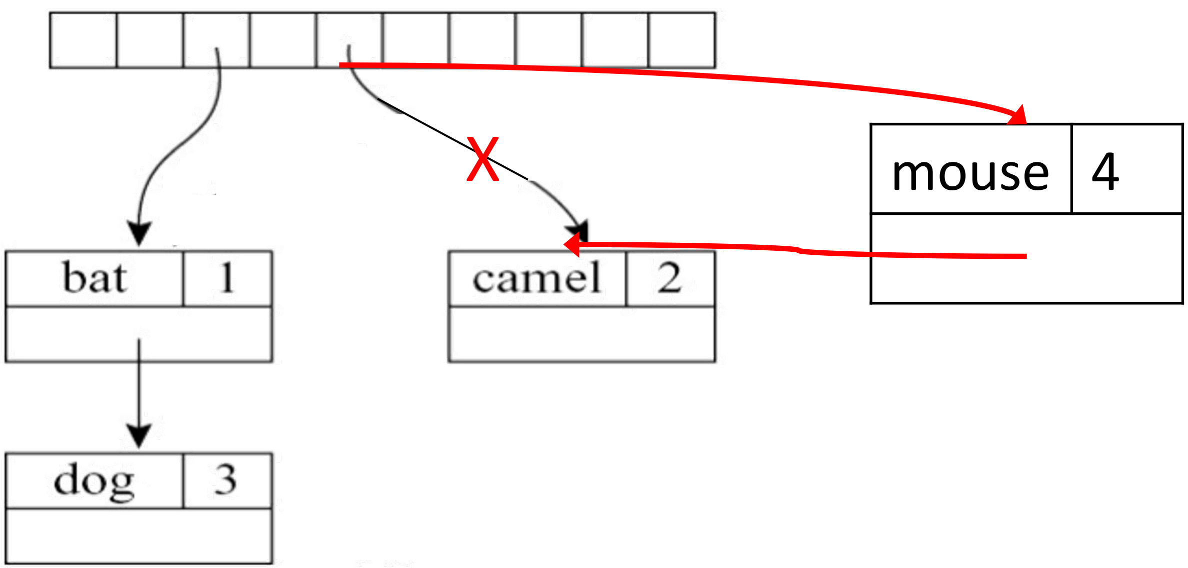
Functional Style

- We wish to compute $\sigma' = \sigma + \{a \mapsto \tau\}$ in such a way that we still have σ available to look up identifiers.
- We create a new table by computing the "sum" of an existing table and a new binding.

- Can we achieve this with hash tables?

Efficient Functional Symbol Tables

- $m2 = m1 + \{mouse \mapsto 4\}$
- $m1 = \{bat \mapsto 1, camel \mapsto 2, dog \mapsto 3\}$, suppose index(camel) = index(mouse) = 5
- Hash(mouse) ==> <mouse, 4>: no longer have m1



Efficient Functional Symbol Tables

- m2 = m1 + {mouse ↦ 4}
- m1 = {bat ↦ 1,camel ↦ 2,dog ↦ 3}, suppose index(camel) = index(mouse) = 5
- Hash(mouse) ==> <mouse, 4>: no longer have m1
- Copy the array, but share all the old buckets: not efficient
  - The array in a hash table should be quite large