CS412/413

Introduction to
Compilers and Translators
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Lecture 19: ADT mechanisms
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Module Mechanisms

- Last time: modules, ways to implement ADTs
- **Module–**collection of related values and types; mechanism for separate compilation, encapsulation, abstraction
- **Record**—set of named fields with types; modules similar to records; module *interface* defines type of module *value*
- **Abstract type**—allows encapsulation of values generated by module
- Implementation known only at link time -- clients are insulated from changes, but harder to optimize

Abstract types

Iota+abstract types, Modula-3 style:

list.int: *declaration of abstract type*

```
type List;
length(l: List): int
cons(h: int, l: List): List
first(l: List): int
rest(l: List): List
```

binding to actual type

list.mod:

```
type List = {len: int, head: int, next: List}
length(l: List): int = l.len
cons(h: int, l: List): List = List{len=l.len+1,head=h,l=l}
...
```


Modules + abstract types

- Module is no longer a record: interface also contains list of abstract types
- Type: module$(I_1..I_n)$ $\{ v_1 : T_1 \ldots v_m : T_m \}$
  $\equiv$ type I_1 ... type I_n
  $v_1 : T_1 \ldots v_m : T_m$
- Stripped-down module syntax:
  type $I_1 = T'_1, \ldots, I_n = T'_n$
  $v_1 : T_1 = e_1 \ldots v_{m'} : T_{m'} = e_{m'}$

How to type-check?

- Additional issues:
  - module must agree with own interface (everything implemented, with right type)
  - must recognize abstract types correctly: add to symbol table
  - You should already do most of this!

$$\frac{A + \{I_i : \text{type} = T'_i\}^{(i\in 1..n)} + \{v_j : T_j\}^{(j\in 1..m')} \vdash e_k : T_k \quad (k\in 1..m') \qquad m' \geq m}{A \vdash \begin{array}{l}\text{type } I_1 = T'_1, \ldots, I_n = T'_n \\ v_1 : T_1 = e_1 \ldots v_{m'} : T_{m'} = e_{m'}\end{array} : \begin{array}{l}\text{module}(I_1..I_n) \\ \{ v_1 : T_1, \ldots, v_m : T_m \}\end{array}}$$

Multiple Implementations

- Most (non-OO) languages: only one implementation of (module value for) any interface
- Doesn't scale to large programs—want multiple modules implementing an interface
- Approach 1: *first-class module values* using *dependent types* (e.g. FX-91 language)
- Approach 2: *objects*

First-class module values

- List interface: ListMod =

```
type T;
length(T): int
cons(int,T): T,
first(T): int
rest(T): T
```

- Two implementations:

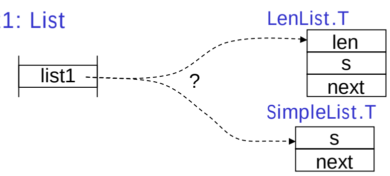
```
SimpleList: ListMod = {
   type T = {head: int, next: T},
   length(l: T): int = (/* recurse */), … }
LenList: ListMod = {
   type T = {len: int, head:int, next: T},
   length(l: T): int = l.len, … }
```


Ambiguity

- Problem: from interface, don't know which implementation we are dealing with.

uses List = ListMod.T

list1: List



Implications

- Must name module value *explicitly* rather than using name of interface: SimpleList.length, LenList.T instead of ListMod.length, ListMod.T
- Code written to use ADT must be passed module value too!

```
sum(list: ListMod, a: list.T): int =
  if (list.length(a) == 0) 0
     else list.first(a) + sum(list, list.rest(a))
```

vs.

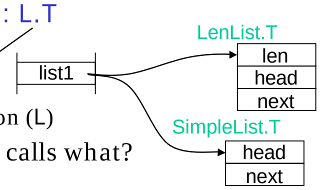
```
sum(a: ListMod.T): int =
   if (ListMod.length(a) == 0) 0
   else ListMod.first(a) + sum(a,…)
```


Compiling Multiple Impls

- Can't stack allocate -- need to know the *concrete type* of a reference (as in C++)
- Don't know what code to run when an operation (e.g. length) is invoked

L: ListMod, list1: L.T

dependent type: contains expression (L)

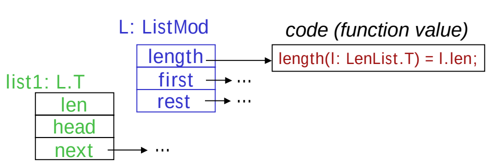


L.length(list1) – calls what?

Using Module Values

- First-class module value is record: points to proper code and global variables of module
- For single implementation (2nd-class modules), linker makes module calls direct

L: ListMod, list1: L.T; L.length(list1)



Using Objects as ADTs

- Another way to extend records into ADTs
- Source code for a class defines the concrete type (implementation)
- Interface defined by public variables and methods of class

```
class List {
   public static int length(List l);
   public static List cons(int, List);
   public static int first(List);
   public static List rest(List);
   private int len, head;
   private List next;
}
```

```
type T;
length(T): int
cons(int,T): T,
first(T): int
rest(T): T
```

Multiple implementations

- Can model using classes and methods:

```
interface List
{  int length();
   List cons(int);
   int first();
   List rest(); }
```

→

```
class SimpleList impls List {
   private int head;
   private SimpleList next;
   public int length()
     { return 1+next.length() } ...
```

↓

```
class LenList implements List {
   private int len, head;
   private LenList next;
   private LenList(int h,t) {...}
   public int length() { return len; }
   public List cons(int h)
       { return new LenList(h, this); } ...
```


The dispatching problem

- Same problem as with first-class modules: don't know what code to run at compile time.

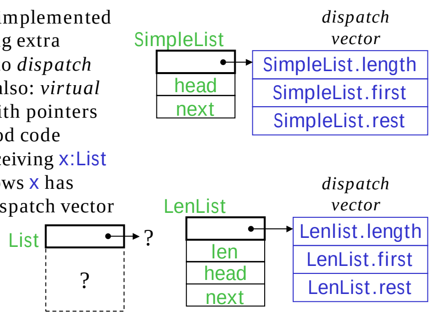
  List a; a.length()

  ListMod L; ListMod.T a; L.length(a)

  ⇒ SimpleList.length or LenList.length?
- Difference: objects "know" their implementation without separate module value (no L needed)

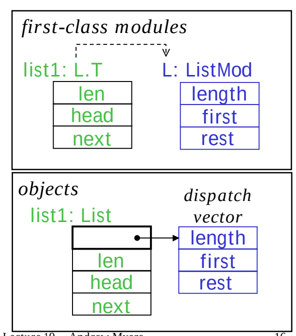
Compiling objects

- Objects implemented by adding extra pointer to *dispatch vector* (also: *virtual table*) with pointers to method code
- Code receiving x:List only knows x has initial dispatch vector pointer



Modules vs. objects

- Objects fold together functionality of records, abstract types and modules
- Both mechanisms allow forms of *polymorphism*: code can use values of more than one type
- Mechanisms have subtly different expressive power



Binary operations

- Advantage of abstract types: compare "LenList" in both styles, but with a binary "prepend" operation:

```
LenList: ListMod = {
   type T = {len: int, head:int, next: T}
   length(l: T): int = l.len
   cons(h: int, l: T): T = {len = l.len+1, ... }
   prepend(l1, l2: T): T = (if (l1.len == 0) l2
        else cons(l1.head, prepend(l1.next, l2)))
}
class LenList implements List {
   len, head: int, next: List
   length() = len
   prepend(l1: List) = ( if (l1.length() == 0) this else
        cons(l1.first(), prepend(l1.rest()))
```

Can't access l1 fields directly!

Heterogeneity

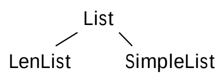
- Objects are better for *heterogenous* data structures containing different implementations of same interface
- Can mix different List impls in same list

Type relationships

- Relationship of LenList module and List interface is relationship of a *value* to its *type*

  LenList, SimpleList : ListMod
- Relationship of classes and object interfaces is more complex... types related by *subtype* relationship
- Enables heterogeneous data structures

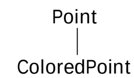
LenList <: List
SimpleList <: List



Subtypes

- Idea: one interface can *extend* another by adding more operations

```
interface Point {
   float x();
   float y();
}
interface ColoredPoint
         extends Point {
   float x();
   float y();
   Color color();
}
```



is a subtype of
ColoredPoint <: Point
(also: ≤)

Subtype properties

If type S is a subtype of type T (S <: T)

- A value of type S may be used wherever a value of type T is expected (*e.g.*, assignment to a variable, passed as argument, returned from method)

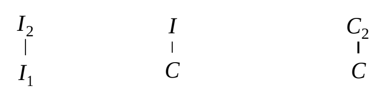
```
Point x;
ColoredPoint y;
...
x = y;
```

ColoredPoint <: Point
subtype *supertype*

- *Subtype polymorphism*: code using T's can also use S's.

Subtypes in Java

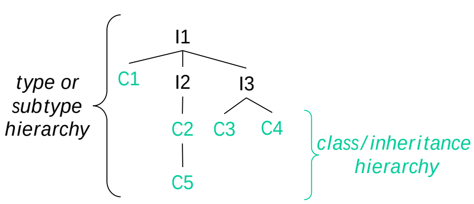
interface *I* extends I_2 { ... }
class *C* implements *I* { ... }
class *C* extends C_2



$I_1 <: I_2$ $\quad C <: I$ $\quad C_1 <: C_2$, C_1 inh C_2

Subtype hierarchy

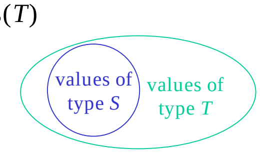
- Introduction of subtype relation creates a hierarchy of types: *subtype hierarchy*



Subtype ≈ Subset

"A value of type S may be used wherever a value of type T is expected"

$S <: T \rightarrow$
$\text{values}(S) \subseteq \text{values}(T)$



Subtyping axioms

- Subtype relation is reflexive: $T <: T$
- Transitive: $$\frac{R <: S \quad S <: T}{R <: T}$$
- Usually anti-symmetric: $$T_1 <: T_2 \wedge T_2 <: T_1 \Rightarrow T_1 = T_2$$
- Defines an ordering on types (partial order)
- Language defines subtype judgement on various type kinds (primitives, records, &c)
- Java: C <: Object, C <: I

Subsumption

- *Subsumption rule* connects subtyping relation and ordinary typing judgements

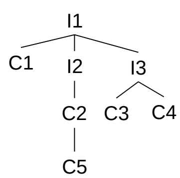
$$\frac{A \vdash E : S \quad S <: T}{A \vdash E : T}$$

S <: T → values(S) ⊆ values(T)

- "If expression E has type S, it also has type T for every T such that S <: T"

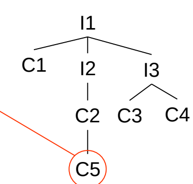
Implementing Type-checking

- Problem: static semantics is supposed to find a type for every expression, but expressions have (in general) many types
- Which type to pick?



Principal Type

- Idea: every expression has a *principal type* that is the most-specific type of the expression



- Can use subsumption rule to infer all supertypes if principal type is used

Type-checking interface

- Old method for checking types:

```
abstract class Node {
    abstract Type typeCheck(SymTab A);
      // Return the principal type of this
      // statement or expression
}
```

- No changes in interface needed to support subtyping, except interpretation of result of typeCheck

Type-checking rules

- Rules for checking code must allow a subtype where a supertype was expected
- Old rule for assignment:

$$\frac{id : T \in A \quad A \vdash E : T}{A \vdash id = E; \ : T}$$

What needs to change here?

Type-checking code

```
class Assignment extends ASTNode {
   String id; Expr E;
   Type typeCheck(SymTab A) {
        Type Tp = E.typeCheck(A);
        Type T = A.lookupVariable(id);
        if (Tp.subtypeOf(T)) return T;
        else throw new TypecheckError(E);
   }
}
```

$$\frac{A \vdash E : T_p \quad T_p <: T}{A \vdash E : T} \;+\; \frac{id : T \in A \quad A \vdash E : T}{A \vdash id = E;\ : T}$$

Unification

- Some rules more problematic: if
- Rule:

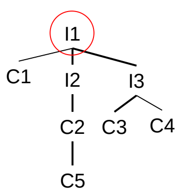
$$\frac{A \vdash E : \mathbf{bool} \quad A \vdash S_1 : T \quad A \vdash S_2 : T}{A \vdash \text{if} (E)\ S_1 \text{ else } S_2 : T}$$

- Problem: suppose S_1 has principal type T_1, S_2 has principal type T_2. Old check: $T_1 = T_2$. New check: need principal type T. How to unify T_1, T_2 ?

Unification in subtype hierarchy

- Idea: unified principal type is least common ancestor in type hierarchy

LCA(C3, C5) = I1



Logic: I1 must be same as or subtype of any type that could be the type of both a value of type C3 and a value of type C5

Explicit vs Structural subtypes

- Java: all subtypes explicitly declared, name equivalence for types. Subtype relationships inferred by transitive extension.
- Languages with structural equivalence (e.g., Modula-3): subtypes inferred based on structure of types; no extends declaration
- Same checking done in each case; explicitly declared subtypes must follow rules for recognizing subtypes implicitly

Testing subtype relation

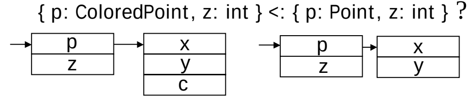
- **Subtyping for records**
  S ≤ T means S has at least the fields of T
  {x: int, y: int, c: Color} <: { x: int, y: int }
- Implementation:

Subtype rule for records

{x: int, y: int, c: Color} ≤ { x: int, y: int }

$$\frac{m \le n}{A \vdash \{a_1 : T_1, \ldots, a_m : T_m\} <: \{a_1 : T_1, \ldots, a_n : T_n\}}$$

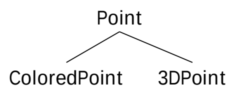
- Similar to our rule for checking modules
- What about allowing field types to vary?
- If Point <: ColoredPoint, allow
  { p: ColoredPoint, z: int } <: { p: Point, z: int } ?



Field Invariance

Try { p: ColoredPoint } <: { p: Point }

```
x: {p: Point}
y: {p: ColoredPoint}
x = y;
x.p = new 3DPoint( );
```

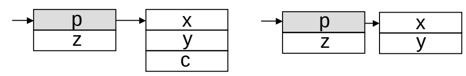


- Mutable (assignable) fields must be *invariant* under subtyping

Covariance

- Immutable record fields *may* change with subtyping (may be *covariant*)
- Suppose we allow variables to be declared *final* -- x : final int
- Safe:

{ p: final ColoredPoint, z: int } ≤ { p: final Point, z: int }



Immutable record subtyping

- Corresponding fields may be subtypes; exact match not required

$$\frac{m \le n \qquad A \vdash T_i <: T'_i \ (i \in 1..m)}{A \vdash \{a_1 : T_1 \ldots a_m : T_m\} <: \{a_1 : T'_1 \ldots a_n : T'_n\}}$$

Summary

- Multiple implementation of abstract types special case of subtyping
- Subtyping characterized by new judgement: $S <: T$
- Old judgement $A \vdash e : T$ plus subsumption rule, defn. of subtype relation defines new type-checking process
- Mutable fields must be invariant in subtype relation; immutable fields may be covariant