CS412/413

Introduction to Compilers
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Lecture 30: Objects
10 Apr 02

Records

- Objects combine features of records and abstract data types
- Records = aggregate data structures
  - Combine several variables (called fields) into a higher-level structure
  - Type is essentially cartesian product of element types
  - Need selection operator to access fields
  - Pascal records, C structures
- Example: struct {int x; float f; char a,b,c; int y } A;
  - Type: {int x; float f; char a,b,c; int y }
  - Selection: A.x = 1; n = A.y;

ADTs

- Abstract Data Types (ADT): separate implementation from specification
  - Specification: provide an abstract type for data
  - Implementation: must match abstract type
- Example: linked list

implementation

```
Cell = { int data; Cell next; }
List = {int len; Cell head, tail; }
int length() { return l.len; }
int first() { return head.data; }
List rest() { return head.next; }
List append(int d) { … }
```

specification

```
int length();
List append (int d);
int first();
List rest();
```

Objects as Records

- Objects also have fields
- … in addition, they have methods = procedures which manipulate the data (fields) in the object
- Hence, objects combine data and computation

```
class List {
      int len;
      Cell head, tail;
      int length();
      List append(int d);
      int first();
      List rest();
}
```

Objects as ADTs

- Specification: public methods and fields of the object
- Implementation: Source code for a class defines the concrete type (implementation)

```
class List {
      private int len;
      private Cell head, tail;
      public static int length() {…};
      public static List append(int d) {…};
      public static int first() {…} ;
      public static List rest() {…};
}
```

Objects

- What objects are:
  - Aggregate structures which combine data (fields) with computation (methods)
  - Fields have public/private qualifiers (can model ADTs)
  - Also referred to as classes
- Objects interfere with almost all compilation stages:
  - Lexical and syntax analysis
  - Semantic analysis (type checking!)
  - Analysis and optimizations
  - Implementation, run-time support
- Features:
  - inheritance, subclassing, subtyping, dynamic dispatch

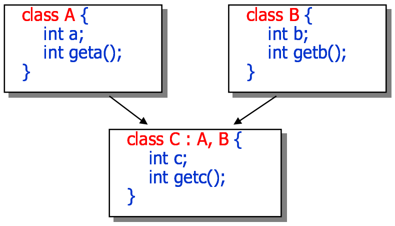
Inheritance

- Inheritance = mechanism which exposes common features of different objects
- Object O1 inherits from O2 = "O1 has the features of O1, plus some additional ones"
  - Say that O2 extends O1

```
class Point {
        float x, y;
        float getx();
        float gety();
}
class ColoredPoint extends Point {
        int color;
        int getcolor();
}
```

Single vs. Multiple Inheritance

- Single inheritance: inherit from only one other object
- Multiple inheritance: inherit from multiple objects



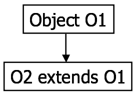
```
class A {
   int a;
   int geta();
}

class B {
   int b;
   int getb();
}

class C : A, B {
   int c;
   int getc();
}
```

Inheritance and Typing

- Inheritance defines a hierarchy between objects
- Objects have types
  - Type is cartesian product of field and method types
- What is the relation between types of parent and inherited objects?

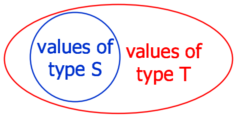


- Subtyping: if O2 extends O1 then
  - Type(O2) is a subtype of Type(O1)
  - Type(O1) is a supertype of Type(O2)
- Notation: Type(O2) <: Type(O1)

Subtype ≈ Subset

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

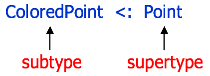
$S <: T \quad \to \quad \text{values}(S) \subseteq \text{values}(T)$



Subtype Properties

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

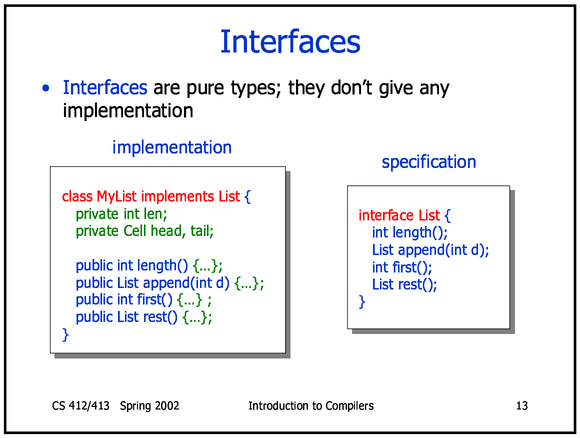
```
Point x;
ColoredPoint y;
x = y;
```



- Polymorphism: a value is usable at several types
- Subtype polymorphism: code using T's can also use S's; S objects can be used as S's or T's.

Objects and Typing

- Objects have types
  - … but also have implementation code for methods
- ADT perspective:
  - Specification = typing
  - Implementation = method code, private fields
  - Objects mix specification with implementation
- Can we separate types from implementation?



Interfaces

- Interfaces are pure types; they don't give any implementation

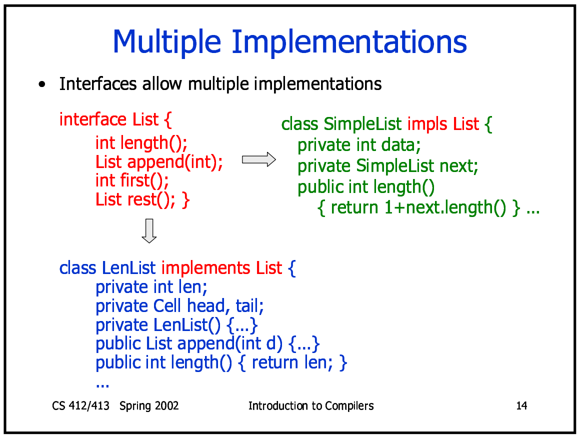
implementation

```
class MyList implements List {
   private int len;
   private Cell head, tail;

   public int length() {…};
   public List append(int d) {…};
   public int first() {…} ;
   public List rest() {…};
}
```

specification

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



Multiple Implementations

- Interfaces allow multiple implementations

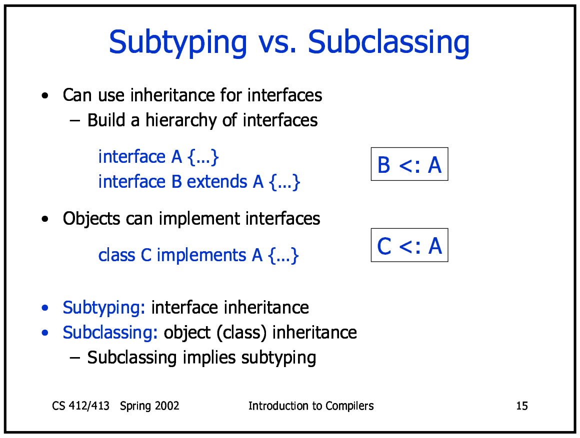
```
interface List {
      int length();
      List append(int);
      int first();
      List rest(); }
```

⇨

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

⇩

```
class LenList implements List {
      private int len;
      private Cell head, tail;
      private LenList() {…}
      public List append(int d) {…}
      public int length() { return len; }
      …
```



Subtyping vs. Subclassing

- Can use inheritance for interfaces
  - Build a hierarchy of interfaces

```
interface A {…}
interface B extends A {…}
```

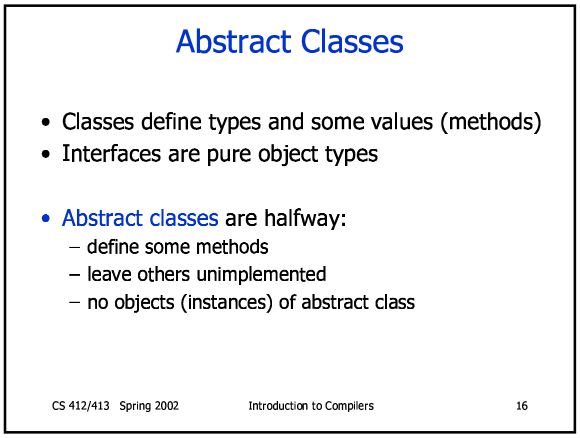
$\boxed{B <: A}$

- Objects can implement interfaces

```
class C implements A {…}
```

$\boxed{C <: A}$

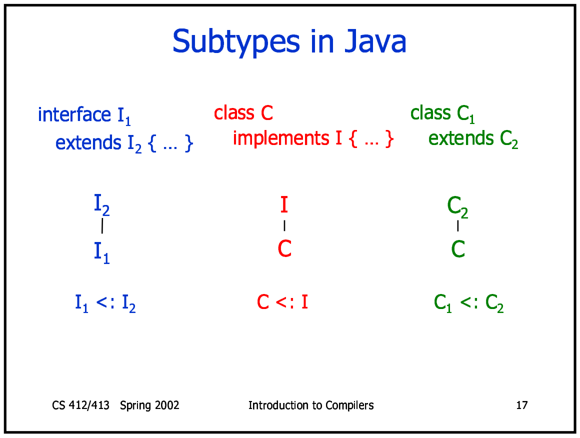
- Subtyping: interface inheritance
- Subclassing: object (class) inheritance
  - Subclassing implies subtyping



Abstract Classes

- Classes define types and some values (methods)
- Interfaces are pure object types

- Abstract classes are halfway:
  - define some methods
  - leave others unimplemented
  - no objects (instances) of abstract class



Subtypes in Java

interface I_1
extends I_2 { … }

class C
implements I { … }

class C_1
extends C_2

I_2
|
I_1

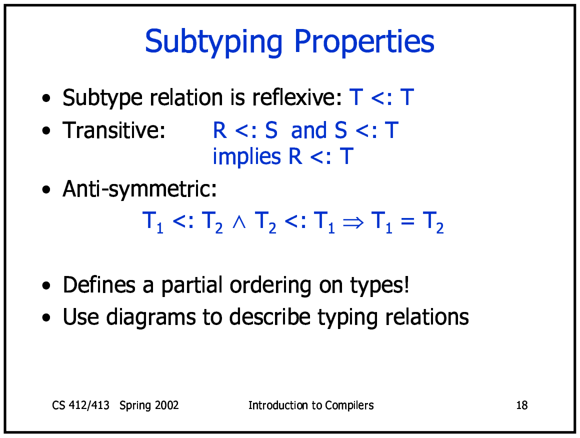
I
|
C

C_2
|
C

$I_1 <: I_2$

$C <: I$

$C_1 <: C_2$



Subtyping Properties

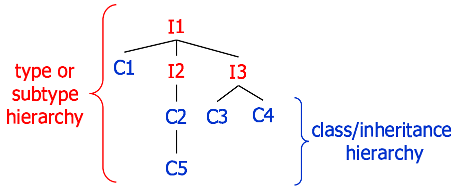
- Subtype relation is reflexive: $T <: T$
- Transitive: $R <: S$ and $S <: T$ implies $R <: T$
- Anti-symmetric:

$$T_1 <: T_2 \wedge T_2 <: T_1 \Rightarrow T_1 = T_2$$

- Defines a partial ordering on types!
- Use diagrams to describe typing relations

Subtype Hierarchy

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



Type-checking

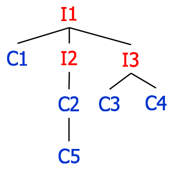
- Problem: what are the valid types for an object?
- Subsumption rule connects subtyping relation and ordinary typing judgements

$$\frac{A \vdash E : S \qquad S <: T}{A \vdash E : T} \qquad S <: T \rightarrow \text{values}(S) \subseteq \text{values}(T)$$

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

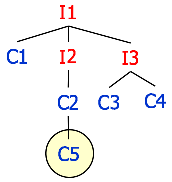
Implementing Type-checking

- Next problem: static semantics is supposed to find a type for every expression, but objects may 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 Overview

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

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

What needs to change here?

Type-checking Overview

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

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

Type-checking Code

```
class Assignment extends ASTNode {
   Variable var; ExprNode E;
   Type typeCheck() {
        Type Tp = E.typeCheck();
        Type T = var.getType();
        if (Tp.subtypeOf(T)) return T;
        else throw new TypecheckError(E); }}
```

$$\frac{A \vdash E : T_p \qquad T_p <: T \qquad id : T \in A}{A \vdash id = E : T}$$

The Dispatching Problem

- Problem: don't know what code to run at compile time!

```
List a;
if (cond)  { a = new SimpleList(); }
else       { a = new LenList(); }
a.length()
```

⇒ SimpleList.length() or LenList.length() ?

- Objects must "know" their implementation at run time
- Method invocations must be resolved dynamically

- Dynamic dispatch: run-time mechanism to select the appropriate method, depending on the object type

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Implementing Dynamic Dispatch

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