CSE341: Programming Languages

Lecture 24
Subtyping

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Last major topic: Subtyping

Build up key ideas from first principles
   – In pseudocode because:
     • No time for another language
     • Simpler to first show subtyping without objects

Then:

• How does subtyping relate to types for OOP?
  – Brief sketch only

• What are the relative strengths of subtyping and generics?

• How can subtyping and generics combine synergistically?
A tiny language

- Can cover most core subtyping ideas by just considering
  *records with mutable fields*

- Will make up our own syntax
  - ML has records, but no subtyping or field-mutation
  - Racket and Ruby have no type system
  - Java uses class/interface names and rarely fits on a slide
Records (half like ML, half like Java)

Record creation (field names and contents):

\{f_1 = e_1, f_2 = e_2, \ldots, f_n = e_n\} \quad \text{Evaluate } e_i, \text{ make a record}

Record field access:

\texttt{e.f} \quad \text{Evaluate } e \text{ to record } v \text{ with an } f \text{ field, get contents of } f \text{ field}

Record field update

\texttt{e_1.f = e_2} \quad \text{Evaluate } e_1 \text{ to a record } v_1 \text{ and } e_2 \text{ to a value } v_2; \quad \text{Change } v_1's \ f \text{ field (which must exist) to } v_2; \quad \text{Return } v_2
A Basic Type System

Record types: What fields a record has and type for each field

\{f_1:t_1, f_2:t_2, \ldots, f_n:t_n\}

Type-checking expressions:

- If \(e_1\) has type \(t_1\), \ldots, \(e_n\) has type \(t_n\),
  then \(\{f_1=e_1, \ldots, f_n=e_n\}\) has type \(\{f_1:t_1, \ldots, f_n:t_n\}\)

- If \(e\) has a record type containing \(f : t\),
  then \(e.f\) has type \(t\)

- If \(e_1\) has a record type containing \(f : t\) and \(e_2\) has type \(t\),
  then \(e_1.f = e_2\) has type \(t\)
This is safe

These evaluation rules and typing rules prevent ever trying to access a field of a record that does not exist.

Example program that type-checks (in a made-up language):

```plaintext
fun distToOrigin (p:{x:real,y:real}) =
    Math.sqrt(p.x*p.x + p.y*p.y)

val pythag : {x:real,y:real} = {x=3.0, y=4.0}
val five : real = distToOrigin(pythag)
```
Motivating subtyping

But according to our typing rules, this program does not type-check
– It does nothing wrong and seems worth supporting

```haskell
fun distToOrigin (p:{x:real,y:real}) =
    Math.sqrt(p.x*p.x + p.y*p.y)

val c : {x:real,y:real,color:string} =
    {x=3.0, y=4.0, color="green"}

val five : real = distToOrigin(c)
```
A good idea: allow extra fields

Natural idea: If an expression has type
\[ \{f_1:t_1, f_2:t_2, \ldots, f_n:t_n\} \]
Then it can also have a type with some fields removed

This is what we need to type-check these function calls:

```scala
fun distToOrigin (p:{x:real,y:real}) = ...  
fun makePurple (p:{color:string}) =  
   p.color = "purple"  
val c :{x:real,y:real,color:string} =  
   {x=3.0, y=4.0, color="green"}
val _ = distToOrigin(c)  
val _ = makePurple(c)
```
Keeping subtyping separate

A programming language already has a lot of typing rules and we do not want to change them

- Example: The type of an actual function argument must equal the type of the function parameter

We can do this by adding “just two things to our language”

- Subtyping: Write $t_1 <: t_2$ for $t_1$ is a subtype of $t_2$
- One new typing rule that uses subtyping:
  If $e$ has type $t_1$ and $t_1 <: t_2$,
  then $e$ (also) has type $t_2$

Now all we need to do is define $t_1 <: t_2$
Subtyping is not a matter of opinion

• Misconception: If we are making a new language, we can have whatever typing and subtyping rules we want

• Not if you want to prevent what you claim to prevent [soundness]
  – Here: No accessing record fields that do not exist

• Our typing rules were sound before we added subtyping
  – We should keep it that way

• Principle of substitutability: If $t_1 <: t_2$, then any value of type $t_1$ must be usable in every way a $t_2$ is
  – Here: Any value of subtype needs all fields any value of supertype has
Four good rules

For our record types, these rules all meet the substitutability test:

1. “Width” subtyping: A supertype can have a subset of fields with the same types
2. “Permutation” subtyping: A supertype can have the same set of fields with the same types in a different order
3. Transitivity: If $t_1 <: t_2$ and $t_2 <: t_3$, then $t_1 <: t_3$
4. Reflexivity: Every type is a subtype of itself

(4) may seem unnecessary, but it composes well with other rules in a full language and “does no harm”
More record subtyping?

[Warning: I am misleading you 😊]

Subtyping rules so far let us drop fields but not change their types

Example: A circle has a center field holding another record

```scala
fun circleY (c:{center:{x:real,y:real}, r:real}) =
    c.center.y
val sphere:{center:{x:real,y:real,z:real}, r:real} =
    {center={x=3.0,y=4.0,z=0.0}, r=1.0}
val _ = circleY(sphere)
```

For this to type-check, we need:

```scala
{center:{x:real,y:real,z:real}, r:real} <: {center:{x:real,y:real}, r:real}
```
Do not have this subtyping – could we?

\[
\{\text{center:\{x:real,y:real,z:real\}}, r:\text{real}\} \\
\ \\
<: \\
\{\text{center:\{x:real,y:real\}}, r:\text{real}\}
\]

- No way to get this yet: we can drop center, drop r, or permute order, but cannot “reach into a field type” to do subtyping

- So why not add another subtyping rule… “Depth” subtyping: If \( ta <: tb \), then \( \{f_1:t_1, \ldots, f:ta, \ldots, fn:tn\} <: \{f_1:t_1, \ldots, f:tb, \ldots, fn:tn\} \)

- Depth subtyping (along with width on the field's type) lets our example type-check
Stop!

- It is nice and all that our new subtyping rule lets our example type-check

- But it is not worth it if it breaks soundness
  - Also allows programs that can access missing record fields

- Unfortunately, it breaks soundness 😞
Mutation strikes again

If ta <: tb,
then {f1:t1, …, f:ta, …, fn:tn} <: {f1:t1, …, f:tb, …, fn:tn}

fun setToOrigin (c:{center:{x:real,y:real}, r:real}) =
c.center = {x=0.0, y=0.0}

val sphere:{center:{x:real,y:real,z:real}, r:real} =
{center={x=3.0, y=4.0, z=0.0}, r=1.0}

val _ = setToOrigin(sphere)
val _ = sphere.center.z (* kaboom! (no z field) *)
Moral of the story

• In a language with records/objects with getters and setters, depth subtyping is unsound
  – Subtyping cannot change the type of fields

• If fields are immutable, then depth subtyping is sound!
  – Yet another benefit of outlawing mutation!
  – Choose two of three: setters, depth subtyping, soundness

• Remember: subtyping is not a matter of opinion
Picking on Java (and C#)

Arrays should work just like records in terms of depth subtyping

- But in Java, if \( t_1 <: t_2 \), then \( t_1[] <: t_2[] \)
- So this code type-checks, surprisingly

```java
class Point { ... }
class ColorPoint extends Point { ... }
...
void m1(Point[] pt_arr) {
    pt_arr[0] = new Point(3,4);
}
String m2(int x) {
    ColorPoint[] cpt_arr = new ColorPoint[x];
    for(int i=0; i < x; i++)
        cpt_arr[i] = new ColorPoint(0,0,"green");
    m1(cpt_arr); // !
    return cpt_arr[0].color; // !
}
```
Why did they do this?

• More flexible type system allows more programs but prevents fewer errors
  – Seemed especially important before Java/C# had generics

• Good news: despite this “inappropriate” depth subtyping
  – `e.color` will never fail due to there being no `color` field
  – Array reads `e1[e2]` always return a (subtype of) `t` if `e1` is a `t[]`

• Bad news: to get the good news
  – `e1[e2]=e3` can fail even if `e1` has type `t[]` and `e3` has type `t`
  – Array stores check the run-time class of `e1`'s elements and do not allow storing a supertype
  – No type-system help to avoid such bugs / performance cost
So what happens

void \texttt{m1}(\texttt{Point}[] \ \texttt{pt}\_\texttt{arr}) \ { \\
\hspace{1em} \texttt{pt}\_\texttt{arr}[0] \ = \ \texttt{new} \ \texttt{Point}(3, 4); \ \texttt{// can throw} \\
} \\
\texttt{String} \ \texttt{m2}(\texttt{int} \ x) \ { \\
\hspace{1em} \texttt{ColorPoint}[] \ \texttt{cpt}\_\texttt{arr} \ = \ \texttt{new} \ \texttt{ColorPoint}[x]; \\
\hspace{1em} \ldots \\
\hspace{1em} \texttt{m1}(%\texttt{cpt}\_\texttt{arr}); \ \texttt{// "inappropriate" depth subtyping} \\
\hspace{1em} \texttt{ColorPoint} \ \texttt{c} \ = \ \texttt{cpt}\_\texttt{arr}[0]; \ \texttt{// fine, \texttt{cpt}\_\texttt{arr}} \\
\hspace{1em} \texttt{// will always hold (subtypes of) \texttt{ColorPoints}} \\
\hspace{1em} \texttt{return} \ \texttt{c}.\texttt{color}; \ \texttt{// fine, a \texttt{ColorPoint} has a color} \\
} \\

- Causes code in \texttt{m1} to throw an \texttt{ArrayStoreException} \\
  - Even though logical error is in \texttt{m2} \\
  - At least run-time checks occur only on array stores, not on field accesses like \texttt{c}.\texttt{color}
null

• Array stores probably the most surprising choice for flexibility over static checking

• But null is the most common one in practice
  – null is not an object; it has no fields or methods
  – But Java and C# let it have any object type (backwards, huh?!)  
  – So, in fact, we do not have the static guarantee that evaluating e in e.f or e.m(...) produces an object that has an f or m
  – The “or null” caveat leads to run-time checks and errors, as you have surely noticed

• Sometimes null is convenient (like ML's option types)
  – But also having “cannot be null” types would be nice
Now functions

• Already know a caller can use subtyping for arguments passed
  – Or on the result

• More interesting: When is one function type a subtype of another?
  – Important for higher-order functions: If a function expects an argument of type \( t_1 \rightarrow t_2 \), can you pass a \( t_3 \rightarrow t_4 \) instead?
  – Coming next: Important for understanding methods
    • (An object type is a lot like a record type where “method positions” are immutable and have function types)
Example

```ocaml
fun distMoved (f : {x:real,y:real}->{x:real,y:real},
      p : {x:real,y:real}) =
  let val p2 : {x:real,y:real} = f p
  val dx : real = p2.x - p.x
  val dy : real = p2.y - p.y
  in Math.sqrt(dx*dx + dy*dy) end

fun flip p = {x = ~p.x, y=~p.y}
val d = distMoved(flip, {x=3.0, y=4.0})
```

No subtyping here yet:
- `flip` has exactly the type `distMoved` expects for `f`
- Can pass `distMoved` a record with extra fields for `p`, but that's old news
Return-type subtyping

fun distMoved (f : {x:real,y:real}->{x:real,y:real},
             p : {x:real,y:real}) =
    let val p2 : {x:real,y:real} = f p
    in
        val dx : real = p2.x - p.x
        val dy : real = p2.y - p.y
        Math.sqrt(dx*dx + dy*dy)
    end

fun flipGreen p = {x = ~p.x, y=~p.y, color="green"}
val d = distMoved(flipGreen, {x=3.0, y=4.0})

• Return type of flipGreen is {x:real,y:real,color:string},
  but distMoved expects a return type of {x:real,y:real}

• Nothing goes wrong: If ta <: tb, then t->ta <: t->tb
  – A function can return “more than it needs to”
  – Jargon: “Return types are covariant”
fun distMoved (f : {x:real,y:real}->{x:real,y:real}, 
    p : {x:real,y:real}) = 
    let val p2 : {x:real,y:real} = f p 
    val dx : real = p2.x - p.x 
    val dy : real = p2.y - p.y 
    in Math.sqrt(dx*dx + dy*dy) end

fun flipIfGreen p = if p.color = "green" (*kaboom!*)
    then {x = ~p.x, y=~p.y}
    else {x = p.x, y=p.y}
val d = distMoved(flipIfGreen, {x=3.0, y=4.0})

- Argument type of flipIfGreen is 
  {x:real,y:real,color:string}, but it is called with a 
  {x:real,y:real}

- Unsound! ta <: tb does NOT allow ta -> t <: tb -> t
The other way works!

```ml
fun distMoved (f : {x:real,y:real}->{x:real,y:real},
    p : {x:real,y:real}) =
  let val p2 : {x:real,y:real} = f p
  val dx : real = p2.x - p.x
  val dy : real = p2.y - p.y
  in Math.sqrt(dx*dx + dy*dy) end

fun flipX_Y0 p = {x = ~p.x, y=0.0}
val d = distMoved(flipX_Y0, {x=3.0, y=4.0})
```

- Argument type of `flipX_Y0` is `{x:real}`, but it is called with a `{x:real,y:real}`, which is fine

- If `tb <: ta`, then `ta -> t <: tb -> t`
  - A function can assume “less than it needs to” about arguments
  - Jargon: “Argument types are contravariant”
Can do both

```plaintext
fun distMoved (f : {x:real,y:real}->{x:real,y:real}, p : {x:real,y:real}) = 
  let val p2 : {x:real,y:real} = f p
  val dx : real = p2.x - p.x
  val dy : real = p2.y - p.y
  in Math.sqrt(dx*dx + dy*dy) end

fun flipXMakeGreen p = {x = ~p.x, y=0.0, color="green"}
val d = distMoved(flipXMakeGreen, {x=3.0, y=4.0})
```

• **flipXMakeGreen** has type
  
  `{x:real} -> {x:real,y:real,color:string}`

• Fine to pass a function of such a type as function of type
  
  `{x:real,y:real} -> {x:real,y:real}`

• If t3 <: t1 and t2 <: t4, then t1 -> t2 <: t3 -> t4
Conclusion

• If \( t_3 <: t_1 \) and \( t_2 <: t_4 \), then \( t_1 \rightarrow t_2 <: t_3 \rightarrow t_4 \)
  – Function subtyping contravariant in argument(s) and covariant in results

• Also essential for understanding subtyping and methods in OOP

• Most unintuitive concept in the course
  – Smart people often forget and convince themselves covariant arguments are okay
  – These people are always mistaken
  – At times, you or your boss or your friend may do this
  – Remember: A guy with a PhD in PL jumped up and down insisting that function/method subtyping is always contravariant in its argument -- covariant is unsound