COS320: Compiling Techniques

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Oat v2

- Specified by a (fairly large) type system
  - $\sim$20 judgements, $\sim$80 inference rules
  - Invest some time in making sure you understand how to read them
- Adds several features to the Oat language:
  - Memory safety
    - *nullable* and *non-null* references. Type system enforces no null pointer dereferences.
    - Run-time array bounds checking (like Java, OCaml)
  - Mutable record types
  - Subtyping

Subtyping

Extrinsic (sub)types

- *Extrinsic view* (Curry-style): a type is a *property* of a term. Think:
  - There is some set of *values*

```
type value =
  | VInt of int
  | VBool of bool
```

  - Each type corresponds to a subset of values

```
let typ_int = function
  | VInt _ -> true
  | _ -> false
let typ_bool = function
  | VBool _ -> true
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```

  - A term has type t if it evaluates to a value of type t

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  - A term has type t if it evaluates to a value of type t
- *Types may overlap*.

```
let typ_nat = function
  | VInt x -> x >= 0
  | _ -> false
```

Subtyping

- Call s a **subtype** of type t if the values of type s is a subset of values of type t
- A subtyping judgement takes the form $\vdash s <: t$
  - "The type s is a subtype of t"
  - Liskov substitution priciple: if s is a subtype of t, then terms of type t can be replaced with terms of type s without breaking type safety.

Barbara Liskov

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$$\frac{}{\vdash \texttt{nat} <: \texttt{int}}\ \textsc{NatInt} \qquad \frac{\Gamma \vdash e : s \qquad \vdash s <: t}{\Gamma \vdash e : t}\ \textsc{Subsumption} \qquad \frac{\vdash t_1 <: t_2 \qquad \vdash t_2 <: t_3}{\vdash t_1 <: t_3}\ \textsc{Transitivity} \qquad \frac{}{\vdash t <: t}\ \textsc{Reflexivity}$$

- Subsumption: if s is a subtype of t, then terms of type s can be used as if they were terms of type t

Casting

- *Upcasting*: Suppose $s <: t$ and e has type s. May safety cast e to type t.
  - Subsumption rule: upcast implicitly (C, C++, Java, ...)
    - Not necessarily a no-op (e.g., upcast int to float)
  - In OCaml: upcast e to t with $(e :> t)$ (important for type inference!)
- *Downcasting*: Suppose $s <: t$ and e has type t. May **not** safety cast e to type s.
  - *Checked downcasting*: check that downcasts are safe at runtime (Java, `dynamic_cast` in C++)
    - Type safe – throwing an exception is not the same as a type error
  - *Unchecked downcasting*: `static_cast` in C++
  - *No downcasting*: OCaml

Extending the subtype relation

Tuple

$$\frac{\vdash t_1 <: s_1 \qquad \dots \qquad \vdash t_n <: s_n}{\vdash t_1 * \cdots * t_n <: s_1 * \cdots * s_n}$$

List

$$\frac{\vdash s <: t}{\vdash s\ \texttt{list} <: t\ \texttt{list}}$$

Array

$$\frac{\vdash s <: t}{\vdash s\ \texttt{array} <: t\ \texttt{array}}$$

Extending the subtype relation

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$$\textsc{Array}\ \frac{\vdash s <: t}{\vdash s\ \texttt{array} <: t\ \texttt{array}}$$

- Array subtyping rule is **unsound** (Java!)
  Let $\Gamma = [x \mapsto \texttt{nat array}]$

$$\textsc{Assn}\ \dfrac{\textsc{Sub}\ \dfrac{\textsc{Var}\ \dfrac{}{\Gamma \vdash x : \texttt{nat array}} \quad \textsc{Array}\ \dfrac{\textsc{NatInt}\ \dfrac{}{\texttt{nat} <: \texttt{int}}}{\texttt{nat array} <: \texttt{int array}}}{\Gamma \vdash x : \texttt{int array}} \quad \textsc{Nat}\ \dfrac{}{\Gamma \vdash 0 : \texttt{nat}} \quad \textsc{Int}\ \dfrac{}{\Gamma \vdash -1 : \texttt{int}}}{\Gamma \vdash x[0] := -1}$$

Width subtying

type $point2d$ { x : int, y : int }
type $point3d$ { x : int, y : int, z : int }

- `point2d <: point3d` or `point3d <: point2d`?

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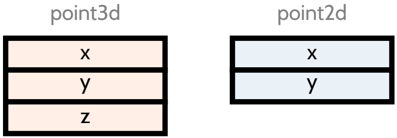
RecordWidth

$$\frac{}{\vdash \{\mathit{lab}_1 : s_1; \ldots; \mathit{lab}_m : s_m\} <: \{\mathit{lab}_1 : s_1; \ldots; \mathit{lab}_n : s_n\}}\ n < m$$

Compiling width subtyping

Easy!

- $s <: t$ means $\texttt{sizeof}(t) \leq \texttt{sizeof}(s)$, but field positions are the same ($e.lab$ compiled the same way, whether e has type s or type t)



- e.g., `pt->y` is `*(pt + sizeof(int))`, regardless of whether `pt` is 2d or 3d

Depth subtyping

type nat_point $\{\ x\ :\ nat,\ \ y\ :\ nat\ \}$
type int_point $\{\ x\ :\ int,\ \ y\ :\ int\ \}$

- `nat_point <: int_point` or `int_point <: nat_point`?

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RecordDepth

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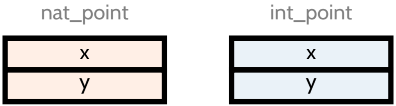
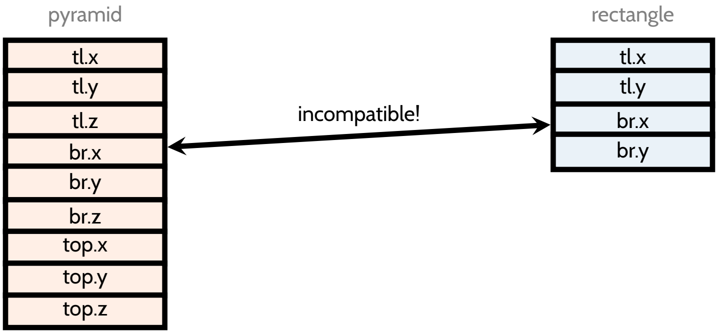


- `pt` is a `nat_point`: `pt->y` is `*(pt + sizeof(nat))`
- `pt` is an `int_point`: `pt->y` is `*(pt + sizeof(int))`
- `sizeof(int) = sizeof(nat)`

Compiling width+depth subtyping

type *point2d* { x : *int*, y : *int* }
type *point3d* { x : *int*, y : *int*, z : *int* }
type *rectangle* = { *tl* : *point2d*, *br* : *point2d* }
type *pyramid* = { *tl* : *point3d*, *br* : *point3d*, *top*: *point3d* }

- Width + depth: `pyramid <: rectangle` (with immutable records)



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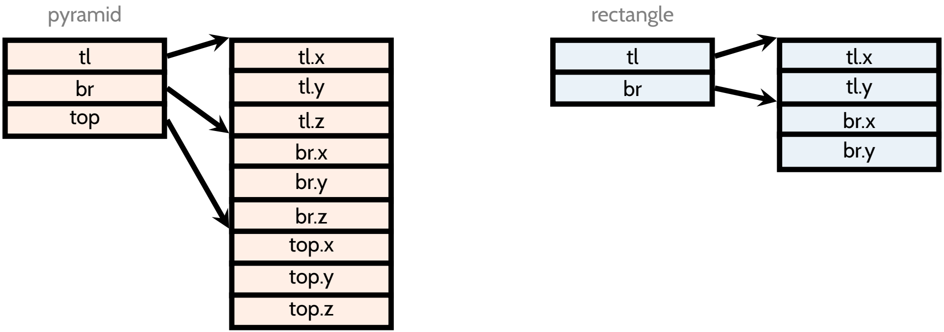

- Add an indirection layer!

Function subtyping

$$\frac{\vdash ? <: ? \qquad \vdash ? <: ?}{\vdash t_1 \rightarrow t_2 <: s_1 \rightarrow s_2}\ \textsc{Fun}$$

Function subtyping

$$\textsc{Fun}\ \frac{\vdash s_1 <: t_1 \qquad \vdash t_2 <: s_2}{\vdash t_1 \to t_2 <: s_1 \to s_2}$$

- In the function subtyping rule, we say that the argument type is *contravariant*, and the output type is *covariant*
- Some languages (Eiffel, Dart) have *covariant* argument subtyping. Not type-safe!

Type inference with subtyping

$$\textsc{Subsumption}\ \frac{\Gamma \vdash e : s \qquad \vdash s <: t}{\Gamma \vdash e : t}$$

- In the presence of the subsumption rule, a term may have more than one type. Which type should we infer?
  - Subtyping forms a *preorder* relation (Reflexivity and Transitivity)
  - Typically (but not necessarily), subtyping is a *partial order*
    - A partial order is a binary relation that is reflexive, transitive, and *antisymmetric*
      If $a <: b$ *and* $b <: a$, *then* $a = b$
    - A preorder that is not a partial order: graph reachability ($u \leq v$ iff there is a path from u to v)

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    - A preorder that is not a partial order: graph reachability ($u \le v$ iff there is a path from u to v)
- Given a context Γ and expression e, goal is to infer **least** type t such that $\Gamma \vdash e : t$ is derivable.

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TYP_CARR

$$\frac{\Gamma \vdash e_1 : t \qquad \ldots \qquad \Gamma \vdash e_n : t}{\Gamma \vdash \texttt{new t[]}\{e_1, \ldots, e_n\} \texttt{ : t[]}}$$

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If

$$\frac{\Gamma \vdash e_1 : \texttt{bool} \qquad \Gamma \vdash e_2 : t \qquad \Gamma \vdash e_3 : t}{\Gamma \vdash \textbf{if } e_1 \textbf{ then } e_2 \textbf{ else } e_3 : t}$$

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- Problem: what is t?
- Say that t is a *least upper bound* of t_2 and t_3 if
  1. $t_2 <: t$ and $t_3 <: t$
  2. For any type t' such that $t_2 <: t'$ and $t_3 <: t'$, we have $t <: t'$

(If $<:$ is a partial order, least upper bound is unique)

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    - Least upper bound is the least common ancestor in class hierarchy

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  - OCaml: no subsumption rule. Must explicitly upcast each side of the branch.

Looking ahead

- Compiling up:
  - Compiling with types, start on optimization
  - HW4: Oat v2
    - Need to implement a type-checker (among other things)
    - (Oat v2 has subtyping)
- A few weeks later: compiling object-oriented languages
  - Subtyping plays a prominent role