Introduction

- Recall for last time: We are inferring types
- Big idea: Replace all concrete type assumptions with type variables
- Collect constraints on these type variables
- Find most general solution for these constraints to deduce types

Quick Refresher

- Let’s quickly look again at one example:
  `let f = lambda x.(f x) in f`

  Type derivation:
  \[
  \Gamma[f \leftarrow a_1][x \leftarrow a_2] \vdash f : a_1 \\
  \Gamma[f \leftarrow a_1][x \leftarrow a_2] \vdash x : a_2 \\
  a_1 = a_2 \rightarrow a_3 \\
  \Gamma[f \leftarrow a_1][x \leftarrow a_2] \vdash (f x) : a_3 \\
  \Gamma[f \leftarrow a_1] \vdash \lambda x.(f x) : a_1 \\
  \Gamma \vdash \text{let } f = \lambda x.(f x) \text{ in } f : a_1
  \]

- Final Type: \( a_1 \) under constraint \( a_1 = a_2 \rightarrow a_3 \)

- This yielded constraint system
  \[
  a_1 = a_2 \rightarrow a_3 \\
  a_1
  \]

Solving Constraints

- Last time, we discussed two substitution rules that allow us to solve such constraints and find the most general solution
- However, the cost of this is quadratic in the number of constraints
- For a large program, this is prohibitive
- Today: How to efficiently solve type constraint systems

Representing Types

- Our type constraint systems are made up of the following three primitives:
  1. Type constants: Int, String
  2. Type variables: \( \alpha_1, \alpha_2 \)
  3. Function Types: \( X \rightarrow Y \)

- Observe that \( X \rightarrow Y \) is just in-fix notation for \( \text{function}(X, Y) \)

- To solve type constraints more efficiently, we will write \( X \rightarrow Y \) as \( \text{function}(X, Y) \), but this is just notation

More Efficient Type Inference

- Big Idea: Maintain equivalence classes of types directly
- Equivalence Class: Set of types that must be equal

- Specifically, if we process constraint of the form \( X = Y \), we know that \( X \) and \( Y \) are equal

- In this case, we want to union the equivalence classes of \( X \) and \( Y \)

- Also, if \( X \) and \( Y \) are function types of the form \( X_1 \rightarrow X_2 \) and \( Y_1 \rightarrow Y_2 \), we also want to union \( X_1 \) and \( Y_1 \) as well as \( X_2 \) and \( Y_2 \)
Union-Find

- To maintain equivalence classes directly, we will use the union-find algorithm.
- Each set of types is called an equivalence class.
- Each set has one element as its representative.
- For type inference: If an equivalence contains a type constant or a function type, we will always use this type as the representative.

Example: Assume following two equivalence classes (representatives in red):
\{int, α\}, \{β → γ, int\}

Example: Union(int, β → γ) results in new equivalence class \{int, α, β → γ\}

Example: Find(α) = int

Union-Find Representation

- We will represent equivalence classes as DAGs.
- Example: \{β → γ, α\}

Conceptually, union will join the dotted areas of two equivalence classes.
And find will return the (red) representative in this class.

Union-Find Representation Cont.

- Consider the following EQs:
  - \(β \rightarrow γ, α\)

And now consider union(β → γ, int)

Finding a Solution from the Union-Find DAG

- Assuming we end up with a consistent Union-find DAG, we can read the most general solution right off!
- For each type variable \(v\), simply return find\((v)\)
- In other words, the representative of each equivalence class is the most general solution.
- Question: Why do we always pick function types or type constants as representatives?
- Question: What happens if a function type and a type constant are in the same equivalence class?
Finding a Solution from the Union-Find DAG

- Example:

![Diagram of Union-Find DAG]

How do we find solution for $\alpha$?

- $\text{find}(\alpha) = \beta \rightarrow \gamma$

- What about $\beta$?

- Every item is in its own EQ, therefore $\text{find}(\beta) = \beta$

Using Union-Find for solving Type Inference Constraints

- Initially, all type variables, functions and type constants are in their own equivalence class.

- We then apply the following function to each equality in our type constraint:

  ```
  bool unify(m, n) {
    s = find(m); t = find(n);
    if(s == t) return true;
    if(s == s1 \rightarrow s2 && t == t1 \rightarrow t2) {
      union(s, t);
      return unify(s1, t1) && unify(s2, t2);
    }
    if(is_variable(s) || is_variable(t)) {
      union(s, t); return true;
    }
    return false; //No solution to type constraints
  }
  ```

Example

- Consider the following system of type constraints:

  $\alpha \rightarrow \text{Int} = \beta$
  $\gamma \rightarrow \text{Int} = \beta$
  $\gamma = \text{String}$

  ![Diagram of type constraints]

  Solution for $\alpha$: $\text{find}(\alpha) = \text{String}$
  Solution for $\beta$: $\text{find}(\beta) = \text{String} \rightarrow \text{Int}$
  Solution for $\gamma$: $\text{find}(\gamma) = \text{String}$

Example Cont

- Consider the following system of type constraints:

  $\alpha = \text{Int} \rightarrow \text{Int}$
  $\alpha = \text{String}$

  ![Diagram of type constraints]

  Conflict: Unify returns false when trying to unify $\text{Int} \rightarrow \text{Int}$ and $\text{String}$

  Conclusion: This system of type constraints is unsatisfiable

Union-Find

- With this new approach, we can now only process each equality once.

- However, for this to be efficient, union/find must be efficient.

- Key result from algorithms: It is possible to build a data structure for union-find that can find a solution to our sets of type constraints in approximately linear time.

- You can learn about this data structure in Advanced Algorithms or Isil’s class on automated logical reasoning.

- But for our purposes, we will just use this data structure.
Type Inference

- If we use Union-Find, we can make type inference practical on real programs
- This style of polymorphic type inference we studied is known as Hindley-Milner type inference
- Type inference is at the core of languages such as OCAML and Haskell
- Type inference is increasingly moving to mainstream languages
  - New C++11 standard
  - Java 7

Type Inference and Errors

- We saw that we can detect all errors easily when doing type inference
- Specifically, every error resulted from unifying two equivalence classes that could not be unified.
- Example: Trying to unify String and $\alpha \rightarrow \text{Int}$
- But how do we report this error to programmers?

Error Reporting

- Consider again the example: String and $\alpha \rightarrow \text{Int}$.
- Option 1: Output message: String and $\alpha \rightarrow \text{Int}$ cannot be unified.
- Is this helpful?
- Obvious problems:
  - Not associated with any source location
  - Understanding typing errors requires understanding type inference

Error Reporting Cont.

- Improvement used in practice: Associate expression/source location with type constraint.
- Message can now at least contain the program expressions that evaluate to String and $\alpha \rightarrow \text{Int}$
- But the actual error in your program may be arbitrarily far from these locations!
- Typical OCaml error:
  "At line 37: Expected expression of type 'a -> 'a but found expression of type 'a -> 'b"
  - To fix this, you need to understand all the reasoning steps that happened during type inference
  - Most likely, the problem did not originate at line 37!

Type Annotations

- Most common technique for mitigating these difficulties:
  - Allow type annotations
- Type annotations allow you explicitly declare types even though the compiler can infer them automatically
- Idea: If you encounter a type error you do not understand, you give the type you expect to the expressions involved in this error and re-run the type checker
- You will now get a new type error in a different location
- You repeat this process until you fixed your type error

Type Annotations Drawbacks

- However, this approach still has substantial drawbacks:
  - You often need many annotations to find the source of type errors
  - You can only annotate successfully if you understand polymorphic type inference
  - You often end up with a program that is almost completely type annotated!
Type Inference in the Real World

- Despite these difficulties, there are many real languages that support full type inference.
- **Examples:** OCaml, Haskell, F#
- **Slogan on Type Inference:** The ease of dynamic typing with the speed and guarantees of a static type system
- This claim is true, but real problems with explaining typing errors to programmers
- Explaining typing errors better is also an active research area!

Type Inference in the Real World Cont.

- Alternative approach taken by more main-stream languages recently: **local type inference**
- In local type inference, types are only inferred within one function, but must be fully annotated at function boundaries.
- **Goal:** Make it easier for programmers to diagnose type errors (and make type inference tractable in the imperative setting)

Example of local type inference

- C++ supports some forms of local type inference.
- **First Example:** templates
  - A STL pair is templatized over the type of the first and second element
  - You declare a pair as: `pair<int, string> p(3, "duck");`
  - However, if you call a function that takes a pair, the compiler will infer the template type for you in some cases:
    - Example: `edit_pair(p)` instead of `edit_pair<pair<int, string>>(p)`

Type Inference in C++

- The `auto` keyword really just says “do type inference on this expression and figure the type out”
- Very convenient, local feature that is also creeping into languages such as C# and Java
- You will see more of this in the future

Example of local type inference

- The new C++11 standard supports much more expressive local type inference
- This is done using the `auto` keyword
  - **Example using iterator:** `vector<int> v; ... for(vector<int>::iterator it = v.begin(); it != v.end(); it++) ...
  - **Example using iterator with new auto keyword:** `vector<int> v; ... for(auto it = v.begin(); it != v.end(); it++) ...

Conclusion

- We saw how to use Union-Find to make type inference scalable
- This formulation is one of the classic and elegant results in programming languages, known as Hindley-Milner type inference
- Type inference is most likely coming to your favorite language in the near future, if it is not already there!