Suggesting Valid Substitutions for Typed Holes

Improving discoverability when working with libraries in Haskell

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What are Typed Holes?

- A typed hole is a "hole" denoted by `_` in the code which can be used to find terms that "fit" the hole.
- Available in `GHC` version `7.8.1`
- Let's look at the hole in the following code:

```
f :: [String]
f = _ "hello, world"
```

If you compile with `GHC` version `8.2.1`, you'll get

- `Found hole: _ :: [Char] -> [String]`
- ```
  In the expression: _
  In the expression: _ "hello, world"
  In an equation for ‘f’: f = _ "hello, world"
  ```
- ```
  Relevant bindings include
    f :: [String] (bound at t.hs:2:1)
  ```

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What are Typed Holes?

- The message tells you the type of the hole:
  - `Found hole: _ :: [Char] -> [String]`
- Where it occurs:
  - ```
    In the expression: _
    In the expression: _ "hello, world"
    In an equation for ‘f’: f = _ "hello, world"
    ```
- And any "relevant" bindings in local scope:
  - ```
    Relevant bindings include
      f :: [String] (bound at t.hs:2:1)
    ```

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What are Valid Substitutions?

- A valid substitution is something that you can replace the hole with directly, and the program will type check.
- Will be available in `GHC` version `8.4.1`
- Let's look the following code again.

```
f :: [String]
f = _ "hello, world"
```

- Compiling this will now get you a list of valid substitutions:

```
Valid substitutions include
  lines :: String -> [String]
  words :: String -> [String]
  inits :: [a] -> [[a]]
  read :: Read a => String -> a
  repeat :: a -> [a]
  return :: Monad m => a -> m a
  ...
```

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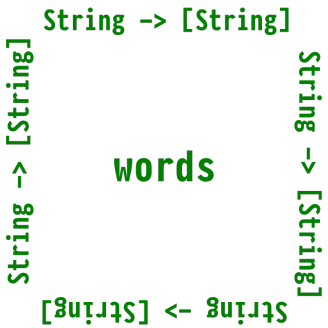
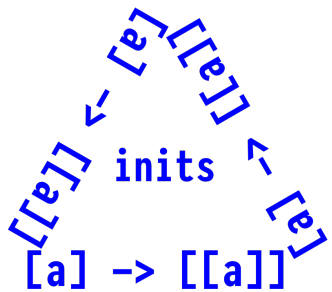
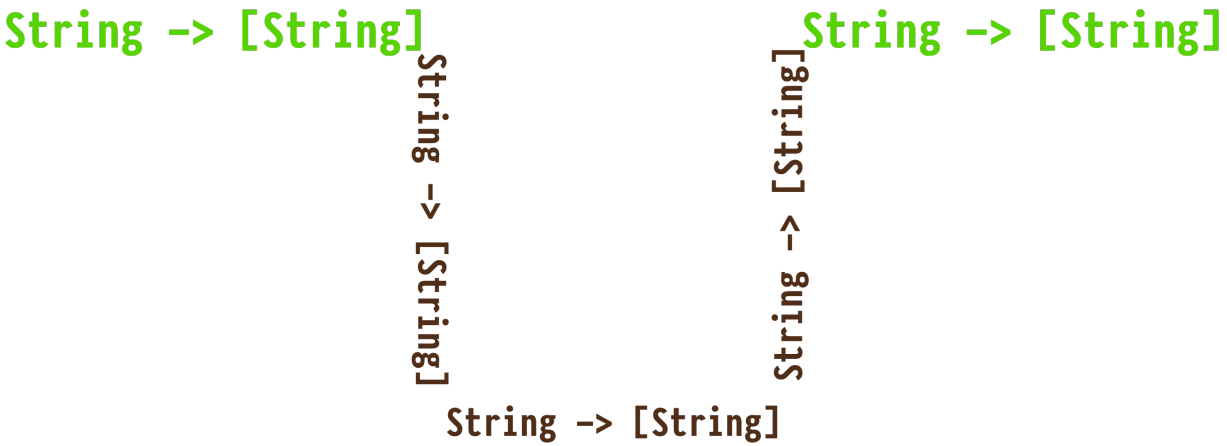
What are Valid Substitutions?

- A valid substitution is not only items with the exact same type of the hole, but polymorphic functions that can be made to fit the hole.







Valid Substitution Demo

DEMO

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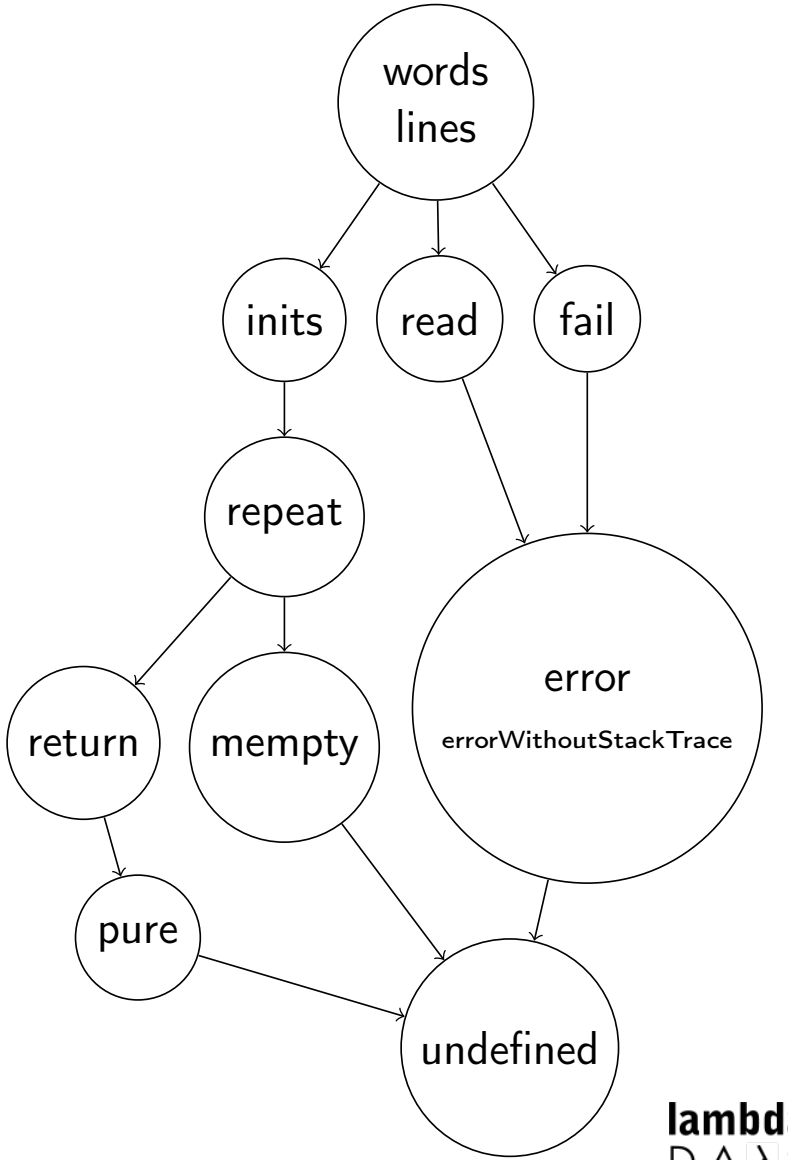
Sorting the Output

- We sort the suggestions by constructing a subsumption graph, and then sorting the suggestions by a topological sort on that graph.
- This makes the most specific suggestions (like `lines` and `words`) appear first, and the more general like `undefined` appear last.



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Refinement Substitutions

- Often when looking for valid substitutions, the answer isn't a single identifier, but a combination of identifiers.
- An example might be `foldl (+) 0` when writing `sum :: [Integer] -> Integer` or `foldl1 max` for `maximum :: [String] -> String`.

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Refinement Substitutions

- A refinement substitution is a valid substitution that has one or more holes in it.
- Will be (probably) be available in `GHC` version `8.6.1`
- When searching for e.g. something of type `[Integer] -> Integer`, a refinement substitution might be `foldl1 _` or `foldl _ _`.
- Using refinement substitutions, we can get progressively closer to the definition we want.

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Refinement Substitutions

- Let's look at the following code:

```
f :: [Integer] -> Integer
f = _ 0
```

- Compiling this with `-frefinement-level-substitutions=1` the compiler will tell us:

```
Valid refinement substitutions include
  foldr _ ::  Foldable t =>
              (a -> b -> b) -> b -> t a -> b
  foldl _ ::  Foldable t =>
              (b -> a -> b) -> b -> t a -> b
```

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How?

- Our extension is based on using the built-in machinery in `GHC` for checking whether one type is a subtype of another.
- By using the already built-in machinery, we can handle large libraries like `lens`, and advance type system features like type families.

DEMO

DEMO

Conclusion

- Valid substitution suggestions for typed holes are useful in many scenarios, for both advanced Haskellers and beginners alike.
- They can help with understanding and learning libraries like the `Prelude` and `lens`.
- They can even help you write secure code!
- Valid substitutions will be available in `8.4.1` (coming soon), while sorting and refinement substitutions are available on `GHC HEAD` and will be released in `8.6.1` later this year.

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Questions?

Thank you!

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Details

- To find these substitutions, we first construct the type of the hole, including any constraints.
- Then, for each identifier in scope, we check whether it can fit the hole.
- We do this by emitting a subtype constraint to the constraint solver, to check that the type of the identifier is a subtype of the hole.
- Since the constraint solver works by doing unification via side-effects, we have to take care to clone any type variables involved, so that they don't get effected the checker.
- We then run the constraints checker, and see if the subtype constraint and any relevant constraints get solved.

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Future Work

- Still buggy! Especially refinement substitutions.
- A search algorithm more akin to what Hoogle does would be nice where they allow some tweaks to the type like changing the number or order of the inputs.
- Consider `f x = (_+x)/5`. Here, `pi :: Floating a => a` is a valid substitution. But since GHC infers that `f` has type of `Fractional a => a -> a`, `pi` gets rejected for not being general enough. Suggesting a tightening (i.e. to a subclass) of inferred constraints when that would give more suggestions would be nice.

Typed Holes Demo Output

Demo1a.hs

```
1  • Found hole: _ :: [Char] -> [String]
2  • In the expression: _
3    In the expression: _ "hello, world"
4    In an equation for ‘f’: f = _ "hello, world"
5  • Relevant bindings include
6      f :: [String] (bound at Demo1.hs:6:1)
```

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Typed Holes Demo Output

Demo1b.hs

```
1  • Found hole: _a :: (Char -> Bool) -> [Char] -> String
2    Or perhaps ‘_a’ is mis-spelled, or not in scope
3  • In the expression: _a
4    In the expression:
5      _a (_b :: Char -> Bool) "hello, world"
6    In an equation for ‘g’:
7      g = _a (_b :: Char -> Bool) "hello, world"
8  • Relevant bindings include
9      g :: String (bound at TypedHolesDemo/Demo1b.hs:7:1)
10
11 • Found hole: _b :: Char -> Bool
12   Or perhaps ‘_b’ is mis-spelled, or not in scope
13 • In the first argument of ‘_a’,
14     namely ‘(_b :: Char -> Bool)’
15   In the expression:
16     _a (_b :: Char -> Bool) "hello, world"
17   In an equation for ‘g’:
18     g = _a (_b :: Char -> Bool) "hello, world"
19 • Relevant bindings include
20     g :: String (bound at TypedHolesDemo/Demo1b.hs:7:1)
```

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Typed Holes Demo Output

Demo1c.hs

```
1   • Found hole: _ :: a0
2     Where: ‘a0’ is an ambiguous type variable
3   • In the first argument of ‘show’, namely ‘_’
4     In the expression: show _
5     In an equation for ‘h’: h = show _
6   • Relevant bindings include
7       h :: String (bound at TypedHolesDemo/Demo1c.hs:4:1)
```

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Valid Substitutions Demo Output

Demo1a.hs

```
1   • Found hole: _ :: [Char] -> [String]
2   • In the expression: _
3     In the expression: _ "hello, world"
4     In an equation for ‘f’: f = _ "hello, world"
5   • Relevant bindings include
6       f :: [String] (bound at Demo1.hs:6:1)
7     Valid substitutions include
8       lines :: String -> [String]
9       words :: String -> [String]
10      group :: forall a. Eq a => [a] -> [[a]]
11      inits :: forall a. [a] -> [[a]]
12      permutations :: forall a. [a] -> [[a]]
13      subsequences :: forall a. [a] -> [[a]]
14      (Some substitutions suppressed;
15        use -fmax-valid-substitutions=N
16        or -fno-max-valid-substitutions)
```

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Valid Substitutions Demo Output

Demo1b.hs: First Hole

```
1   • Found hole: _a :: (Char -> Bool) -> [Char] -> String
2     Or perhaps ‘_a’ is mis-spelled, or not in scope
3   • In the expression: _a
4     In the expression:
5       _a (_b :: Char -> Bool) "hello, world"
6     In an equation for ‘g’:
7       g = _a (_b :: Char -> Bool) "hello, world"
8   • Relevant bindings include
9       g :: String (bound at TypedHolesDemo/Demo1b.hs:7:1)
10    Valid substitutions include
11      filter :: forall a. (a -> Bool) -> [a] -> [a]
12      dropWhile :: forall a. (a -> Bool) -> [a] -> [a]
13      takeWhile :: forall a. (a -> Bool) -> [a] -> [a]
14      dropWhileEnd :: forall a. (a -> Bool) -> [a] -> [a]
15      sortOn :: forall b a. Ord b => (a -> b) -> [a] -> [a]
16      mempty :: forall a. Monoid a => a
17      (Some substitutions suppressed;
18          use -fmax-valid-substitutions=N
19          or -fno-max-valid-substitutions)
```

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Valid Substitutions Demo Output

Demo1b.hs: Second Hole

```
• Found hole: _b :: Char -> Bool
  Or perhaps ‘_b’ is mis-spelled, or not in scope
• In the first argument of ‘_a’,
    namely ‘(_b :: Char -> Bool)’
  In the expression:
    _a (_b :: Char -> Bool) "hello, world"
  In an equation for ‘g’:
    g = _a (_b :: Char -> Bool) "hello, world"
• Relevant bindings include
    g :: String (bound at TypedHolesDemo/Demo1b.hs:7:1)
  Valid substitutions include
    isLetter :: Char -> Bool
    isMark :: Char -> Bool
    isNumber :: Char -> Bool
    isSeparator :: Char -> Bool
    isAlpha :: Char -> Bool
    isAlphaNum :: Char -> Bool
    (Some substitutions suppressed;
        use -fmax-valid-substitutions=N
        or -fno-max-valid-substitutions)
```

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Valid Substitutions Demo Output

Demo1c.hs

```
1   • Found hole: _ :: a0
2     Where: ‘a0’ is an ambiguous type variable
3   • In the first argument of ‘show’, namely ‘_’
4     In the expression: show _
5     In an equation for ‘h’: h = show _
6   • Relevant bindings include
7       h :: String (bound at TypedHolesDemo/Demo1c.hs:4:1)
8     Valid substitutions include
9       h :: String
10      EQ :: Ordering
11      LT :: Ordering
12      GT :: Ordering
13      pi :: forall a. Floating a => a
14      otherwise :: Bool
15      (Some substitutions suppressed;
16          use -fmax-valid-substitutions=N
17          or -fno-max-valid-substitutions)
```

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Lens Demo Output

LensDemo/sr/test.hs

```
1   • Found hole:
2       _a :: ((Integer -> f0 Integer) -> Test -> f0 Test)
3             -> (Integer -> Integer) -> State Test a0
4     Where: ‘f0’ is an ambiguous type variable
5            ‘a0’ is an ambiguous type variable
6   • In the expression: ...
7   • Relevant bindings include ...
8     Valid substitutions include
9       (%=) :: forall s (m :: * -> *) a b.
10                MonadState s m => ASetter s s a b -> (a -> b) -> m ()
11      modifying :: forall s (m :: * -> *) a b.
12                   MonadState s m => ASetter s s a b -> (a -> b) -> m ()
13      (<%=) :: forall s (m :: * -> *) b a.
14               MonadState s m => LensLike ((,) b) s s a b -> (a -> b) -> m b
15      (<#%=) :: forall s (m :: * -> *) a b.
16                MonadState s m => ALens s s a b -> (a -> b) -> m b
17      (#%=) :: forall s (m :: * -> *) a b.
18               MonadState s m => ALens s s a b -> (a -> b) -> m ()
19      uses :: forall s (m :: * -> *) r a.
20              MonadState s m => LensLike' (Const r) s a -> (a -> r) -> m r
21      (Some substitutions suppressed;
22          use -fmax-valid-substitutions=N
23          or -fno-max-valid-substitutions)
```

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Lens Demo Output

LensDemo/src/test.hs

```
• Found hole:
    _b :: ((Integer -> f0 Integer) -> Test -> f1 Test)
          -> Integer -> State Test a1
  Where: ‘f1’ is an ambiguous type variable
         ‘a1’ is an ambiguous type variable
• In the expression: ...
• Relevant bindings include ...
  Valid substitutions include
    (^=) :: forall s (m :: * -> *) a e.
            (MonadState s m, Num a, Integral e) => ASetter' s a -> e -> m ()
    (<.=) :: forall s (m :: * -> *) a b.
             MonadState s m => ASetter s s a b -> b -> m b
    (*=) :: forall s (m :: * -> *) a.
            (MonadState s m, Num a) => ASetter' s a -> a -> m ()
    (+=) :: forall s (m :: * -> *) a.
            (MonadState s m, Num a) => ASetter' s a -> a -> m ()
    (-=) :: forall s (m :: * -> *) a.
            (MonadState s m, Num a) => ASetter' s a -> a -> m ()
    (.=) :: forall s (m :: * -> *) a b.
            MonadState s m => ASetter s s a b -> b -> m ()
    (Some substitutions suppressed;
        use -fmax-valid-substitutions=N
        or -fno-max-valid-substitutions)
```

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Constraints Demo Output

DCC/Example.hs

```
1   • Found hole: _ :: T 'H User -> T 'L a0
2     Where: ‘a0’ is an ambiguous type variable
3   • In the expression: _
4     In the first argument of ‘pure’, namely ‘(_ user)’
5     In a stmt of a 'do' block: info <- pure (_ user)
6   • Relevant bindings include
7       user :: T 'H User (bound at Example.hs:4:11)
8       main :: IO () (bound at Example.hs:4:1)
9     Valid substitutions include
10      isInGothenburg :: T 'H User -> T 'L Bool
11      isAllowedToDrink :: T 'H User -> T 'L Bool
12      bestNearbyRestaurant :: T 'H User -> T 'L (Maybe Restaurant)
```

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Sorting Demo Output

Demo4a.hs

```
1   • Found hole: _ :: [Char] -> [String]
2   • In the expression: _
3     In the expression: _ "hello, world"
4     In an equation for ‘f’: f = _ "hello, world"
5   • Relevant bindings include
6       f :: [String] (bound at TypedHolesDemo/Demo4a.hs:7:1)
7     Valid substitutions include
8       inits :: forall a. [a] -> [[a]]
9       fail :: forall (m :: * -> *). Monad m => forall a. String -> m a
10      mempty :: forall a. Monoid a => a
11      pure :: forall (f :: * -> *). Applicative f => forall a. a -> f a
12      return :: forall (m :: * -> *). Monad m => forall a. a -> m a
13      read :: forall a. Read a => String -> a
14      lines :: String -> [String]
15      words :: String -> [String]
16      error :: forall (a :: TYPE r). HasCallStack => [Char] -> a
17      errorWithoutStackTrace :: forall (a :: TYPE r). [Char] -> a
18      undefined :: forall (a :: TYPE r). HasCallStack => a
19      repeat :: forall a. a -> [a]
```

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Sorting Demo Output

Demo4b.hs

```
1   • Found hole: _ :: [Char] -> [String]
2   • In the expression: _
3     In the expression: _ "hello, world"
4     In an equation for ‘f’: f = _ "hello, world"
5   • Relevant bindings include
6       f :: [String] (bound at TypedHolesDemo/Demo4b.hs:7:1)
7     Valid substitutions include
8       lines :: String -> [String]
9       words :: String -> [String]
10      inits :: forall a. [a] -> [[a]]
11      read :: forall a. Read a => String -> a
12      repeat :: forall a. a -> [a]
13      mempty :: forall a. Monoid a => a
14      return :: forall (m :: * -> *). Monad m => forall a. a -> m a
15      pure :: forall (f :: * -> *). Applicative f => forall a. a -> f a
16      fail :: forall (m :: * -> *). Monad m => forall a. String -> m a
17      error :: forall (a :: TYPE r). HasCallStack => [Char] -> a
18      errorWithoutStackTrace :: forall (a :: TYPE r). [Char] -> a
19      undefined :: forall (a :: TYPE r). HasCallStack => a
```

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Refinement Demo Output

Demo0a.hs

```
1   • Found hole: _ :: Integer -> [Integer] -> Integer
2   • In the expression: _
3     In the expression: _ 0
4     In an equation for ‘f’: f = _ 0
5   • Relevant bindings include
6       f :: [Integer] -> Integer (bound at TypedHolesDemo/Demo0a.hs:4:1)
7     Valid substitutions include
8       const :: forall a b. a -> b -> a
9       undefined :: forall (a :: TYPE r). HasCallStack => a
10    Valid refinement substitutions include
11      foldr _ :: forall (t :: * -> *).
12                 Foldable t =>
13                 forall a b. (a -> b -> b) -> b -> t a -> b
14      foldl _ :: forall (t :: * -> *).
15                 Foldable t =>
16                 forall b a. (b -> a -> b) -> b -> t a -> b
17      head _ :: forall a. [a] -> a
18      last _ :: forall a. [a] -> a
19      error _ :: forall (a :: TYPE r). HasCallStack => [Char] -> a
20      errorWithoutStackTrace _ :: forall (a :: TYPE r). [Char] -> a
21      (Some refinement substitutions suppressed;
22          use -fmax-refinement-substitutions=N
23          or -fno-max-refinement-substitutions)
```

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Refinement Demo Output

Demo0b.hs

```
1   • Found hole: _ :: [Integer] -> Integer
2   • In the expression: _
3     In an equation for ‘f’: f = _
4   • Relevant bindings include
5       f :: [Integer] -> Integer (bound at TypedHolesDemo/Demo0b.hs:4:1)
6     Valid substitutions include
7       f :: [Integer] -> Integer
8       product :: forall (t :: * -> *). Foldable t =>
9                  forall a. Num a => t a -> a
10      sum :: forall (t :: * -> *). Foldable t =>
11             forall a. Num a => t a -> a
12      maximum :: forall (t :: * -> *). Foldable t =>
13                 forall a. Ord a => t a -> a
14      minimum :: forall (t :: * -> *). Foldable t =>
15                 forall a. Ord a => t a -> a
16      head :: forall a. [a] -> a
17      (Some substitutions suppressed;
18        use -fmax-valid-substitutions=N or -fno-max-valid-substitutions)
19    Valid refinement substitutions include
20      foldr _ _ :: forall (t :: * -> *). Foldable t =>
21                   forall a b. (a -> b -> b) -> b -> t a -> b
22      foldl1 _ :: forall (t :: * -> *). Foldable t =>
23                  forall a. (a -> a -> a) -> t a -> a
24      foldr1 _ :: forall (t :: * -> *). Foldable t =>
25                  forall a. (a -> a -> a) -> t a -> a
26      foldl _ _ :: forall (t :: * -> *). Foldable t =>
27                   forall b a. (b -> a -> b) -> b -> t a -> b
28      head _ :: forall a. [a] -> a
29      last _ :: forall a. [a] -> a
30      (Some refinement substitutions suppressed;
31          use -fmax-refinement-substitutions=N or -fno-max-refinement-substitutions)
```

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Refinement Demo Output

Demo0c.hs

```
TypedHolesDemo/Demo0c.hs:6:5: error:
    • Found hole: _ :: String -> [String]
    • In the expression: _
      In an equation for ‘f’: f = _
    • Relevant bindings include
        f :: String -> [String] (bound at TypedHolesDemo/Demo0c.hs:6:1)
      Valid substitutions include
        f :: String -> [String]
        lines :: String -> [String]
        words :: String -> [String]
        group :: forall a. Eq a => [a] -> [[a]]
        inits :: forall a. [a] -> [[a]]
        permutations :: forall a. [a] -> [[a]]
        (Some substitutions suppressed; use -fmax-valid-substitutions=N or -fno-max-valid-substitutions)
      Valid refinement substitutions include
        foldl1' _ _ :: forall a. (a -> a -> a) -> [a] -> a
        unfoldr _ :: forall b a. (b -> Maybe (a, b)) -> b -> [a]
        groupBy _ :: forall a. (a -> a -> Bool) -> [a] -> [[a]]
        (<$) _ :: forall (f :: * -> *).
                  Functor f =>
                  forall a b. a -> f b -> f a
        (<*) _ :: forall (f :: * -> *).
                  Applicative f =>
                  forall a b. f a -> f b -> f a
        mapM _ :: forall (t :: * -> *).
                  Traversable t =>
                  forall (m :: * -> *) a b. Monad m => (a -> m b) -> t a -> m (t b)
        (Some refinement substitutions suppressed;
          use -fmax-refinement-substitutions=N
          or -fno-max-refinement-substitutions)
```

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