Lecture 6(a): Introduction to Static Analysis

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CS4200 Compiler Construction
TU Delft
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TU Delft

Why Type Checking?

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Why Type Checking? Some Discussion Points

Dynamically Typed vs Statically Typed

- Dynamic: type checking at run-time
- Static: type checking at compile-time (before run-time)

What does it mean to type check?

- Type safety: guarantee absence of run-time type errors

Why static type checking?

- Avoid overhead of run-time type checking
- Fail faster: find (type) errors at compile time
- Find all (type) errors: some errors may not be triggered by testing
- But: not all errors can be found statically (e.g. array bounds checking)

Context-Sensitive Properties

Homework Assignment: What is the Syntax of This Language?

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
 </book>
 <book>
  <title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
</catalogue>
```

```
<languages>
 <language>
  <name>SDF3</name>
    <purpose>Syntax Definition</purpose>
    <implementedin>SDF3</implementedin>
 </language>
 <language>
   <name>Stratego</name>
    <purpose>Transformation</purpose>
    <implementedin>SDF3</implementedin>
    <implementedin>Stratego</implementedin>
    <target>Java</target>
 </language>
</languages>
```

Syntax of Book Catalogues

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
 </book>
 <book>
  <title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
</catalogue>
```

```
context-free syntax

  Document.Catalogue = [
    <catalogue>
      [Book*]
    </catalogue>
  ]

  Book.Book = [
    <book>
      [Title]
      [Author]
      [Publisher]
    </book>
  ]

  …
```

Schema-specific syntax definition

A Generic Syntax of XML Documents

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
 </book>
 <book>
  <title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
</catalogue>
```

```
Doc(
  Node(
    "catalogue"
  , [ Node(
        "book"
      , [ Node("title", [Text(["Modern Compiler Implementation in ML"])], "title")
        , Node("author", [Text(["Andrew Appel"])], "author")
        , Node("publisher", [Text(["Cambridge"])], "publisher")
        ]
      , "book"
      )
    , Node(
        "book"
      , [ Node("title", [Text(["Parsing Schemata"])], "title")
        , Node("author", [Text(["Klaas Sikkel"])], "author")
        , Node("publisher", [Text(["Springer"])], "publisher")
        ]
      , "book"
      )
    ]
  , "catalogue"
  )
)
```

```
context-free start-symbols Document

sorts Tag Word
lexical syntax
  Tag  = [a-zA-Z][a-zA-Z0-9]*
  Word = ~[\<\>]+

lexical restrictions
  Word -/- ~[\<\>]

sorts Document Elem
context-free syntax

  Document.Doc = Elem

  Elem.Node = [
    <[Tag]>
      [Elem*]
    </[Tag]>
  ]

  Elem.Text = Word+ {longest-match}
```

A Generic Syntax of XML Documents

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
 </book>
 <book>
  <title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
</catalogue>
```

```
context-free start-symbols Document

sorts Tag Word
lexical syntax
  Tag  = [a-zA-Z][a-zA-Z0-9]*
  Word = ~[\<\>]+

lexical restrictions
  Word -/- ~[\<\>]

sorts Document Elem
context-free syntax

  Document.Doc = Elem

  Elem.Node = [
    <[Tag]>
      [Elem*]
    </[Tag]>
  ]

  Elem.Text = Word+ {longest-match}
```

What is the problem with this approach?

Generic Syntax is Too Liberal!

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
  <year></year>
 </book>
 <language>
  <name>SDF3</name>
    <purpose>Syntax Definition</purpose>
    <implementedin>SDF3</implementedin>
 </language>
 <book>
  //<title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
 <book>
 </koob>
</catalogue>
```

Year is not a valid element of book

Only books in catalogue

Book should have a title

Closing tag is not consistent with starting tag

```
context-free start-symbols Document

sorts Tag Word
lexical syntax
  Tag  = [a-zA-Z][a-zA-Z0-9]*
  Word = ~[\<\>]+

lexical restrictions
  Word -/- ~[\<\>]

sorts Document Elem
context-free syntax

  Document.Doc = Elem

  Elem.Node = [
    <[Tag]>
      [Elem*]
    </[Tag]>
  ]

  Elem.Text = Word+ {longest-match}
```

Context-Sensitive Properties

Context-free grammar is … context-free!

- Cannot express alignment

Languages have context-sensitive properties

How can we have our cake and eat it too?

- Generic (liberal) syntax
- Forbid programs/documents that are not well-formed

Checking Context-Sensitive Properties

Approach: Checking Context-Sensitive Properties

Generic (liberal) syntax

- Allow more programs/documents

Check properties on AST

- Reject programs/documents that are not well-formed

Checking Context-Context-Sensitive Properties in Spoofax

errors.xml

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
  <year></year>
 </book>
 <language>
  <name>SDF3</name>
    <purpose>Syntax Definition</purpose>
    <implementedin>SDF3</implementedin>
 </language>
 <book>
  //<title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
 <book>
 </koob>
</catalogue>
```

parse

```
Doc(
  Node(
    "catalogue"
  , [ Node(
        "book"
      , [ Node("title", [Text(["Modern Compiler Implementation in ML"])], "title")
        , Node("author", [Text(["Andrew Appel"])], "author")
        , Node("publisher", [Text(["Cambridge"])], "publisher")
        , Node("year", [], "year")
        ]
      , "book"
      )
    , Node(
        "language"
      , [ Node("name", [Text(["SDF3"])], "name")
        , Node("purpose", [Text(["Syntax Definition"])], "purpose")
        , Node("implementedin", [Text(["SDF3"])], "implementedin")
        ]
      , "language"
      )
    , Node(
        "book"
      , [ Node("author", [Text(["Klaas Sikkel"])], "author")
        , Node("publisher", [Text(["Springer"])], "publisher")
        ]
      , "book"
      )
    , Node("book", [], "koob")
    ]
```

```
rules // Analysis

  editor-analyze:
    (ast, path, project-path) -> (ast', error*, warning*, info*)
    with
      ast'      := <id> ast
    ; error*    := <collect-all(constraint-error)> ast'
    ; warning*  := <collect-all(constraint-warning)> ast'
    ; info*     := <collect-all(constraint-info)> ast'
```

errors

Check Violations using Constraint-Error Rules

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
  <year></year>
 </book>
 <language>
  <name>SDF3</name>
    <purpose>Syntax Definition</purpose>
    <implementedin>SDF3</implementedin>
 </language>
 <book>
  //<title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
 <book>
 </koob>
</catalogue>
```

Find all sub-terms that are not consistent with the context-sensitive rules

collect-all: type-unifying generic traversal

```
rules // Analysis

  editor-analyze:
    (ast, path, project-path) -> (ast', error*, warning*, info*)
    with
      ast'     := <id> ast
    ; error*   := <collect-all(constraint-error)> ast'
    ; warning* := <collect-all(constraint-warning)> ast'
    ; info*    := <collect-all(constraint-info)> ast'
```

Check Violations using Constraint-Error Rules

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
  <year></year>
 </book>
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 <book>
  //<title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
 <book>
 </koob>
</catalogue>
```

Closing tag does not match starting tag

Origin

Error message

```
rules

  constraint-error :
    Node(tag1, elems, tag2) -> (tag2, $[Closing tag does not match starting tag])
    where <not(eq)>(tag1, tag2)
```

Check Violations using Constraint-Error Rules

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
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 <language>
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 <book>
  //<title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
 <book>
 </koob>
</catalogue>
```

Book should have a title

Containment checks

```
rules

  constraint-error :
    n@Node(tag@"book", elems, _) -> (tag, $[Book should have title])
    where <not(has(|"title"))> elems

  has(|tag) = fetch(?Node(tag, _, _))
```

Check Violations using Constraint-Error Rules

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
  <year></year>
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  //<title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
 <book>
 </koob>
</catalogue>
```

Containment checks

```
Catalogue can only have books
```

```
rules

  constraint-error :
    Node("catalogue", elems, _) -> error
    where <filter(not-a-book)> elems => [error | _]

  not-a-book :
    Node(tag, _, _) -> (tag, $[Catalogue can only have books])
    where <not(eq)> (tag, "book")
```

Check Violations using Constraint-Error Rules

```
<catalogue>
 <book>
  <title>Modern Compiler Implementation in ML</title>
  <author>Andrew Appel</author>
  <publisher>Cambridge</publisher>
  <year></year>
 </book>
 <language>
  <name>SDF3</name>
    <purpose>Syntax Definition</purpose>
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 </language>
 <book>
  //<title>Parsing Schemata</title>
  <author>Klaas Sikkel</author>
  <publisher>Springer</publisher>
 </book>
 <book>
 </koob>
</catalogue>
```

`Book can only have title, author, publisher`

Containment checks

```
rules

  constraint-error :
    Node("book", elems, _) -> error
    where <filter(not-a-book-elem)> elems => [error | _]

  not-a-book-elem :
    Node(tag, _, _) -> (tag, $[Book can only have title, author, publisher])
    where <not(elem())> (tag, ["title", "author", "publisher"])
```

Approach: Checking Context-Sensitive Properties

Generic (liberal) syntax

- Allow more programs/documents
- `permissive syntax’

Check properties on AST

- Reject programs/documents that are not well-formed

Advantage

- Smaller syntax definition
- Parser does not fail (so often)
- Better error messages than parser can give

How are programming languages different from XML?

Programming Languages vs XML

XML checking

- Tag consistency
- Schema consistency
- These are structural properties

Programming languages

- Type consistency (similar to schema?)
- Name consistency: declarations and references should correspond
- Name dependent type consistency: names carry types

Types

Why types?

Why types?

- "guarantee absence of run-time type errors"

What is a type system?

- A type system is a tractable syntactic method for proving the absence of certain program behaviors by classifying phrases according to the kinds of values they compute. [Pierce2002]

Discuss using a series of untyped examples

- Do you consider the example correct or not, and why?
  - That is, do you think it should type-check?
- If incorrect: what types will disallow this program?
- If correct: what types will allow this program?

Preliminaries

```
class A {
    B b;
    int m(int i) {
        return i + b.f;
    }
}

class B {
    int f;
}
```

How do types show up in programs?

- Type literals describe types
- Type definitions introduce new (named) types
- Type references refer to named types
- Declared variables have types (`x : T`)
- Expressions have types (`e : T`)
    - Including all sub-expressions

Types Example

```
4 / "four"
```

```
4       : number
"four"  : string
/       : number * number → number
```

simple types

```
typing prevents undefined runtime behavior
```

Types Example

```
7 + (if (true) { 5 } else { "four" })
```

```
7 : number          "four" : string
5 : number          if     : ?
```

no simple type

```
- typing (over)approximates runtime behavior
- programs without runtime errors can be rejected
```

Types Example

```
function id(x) { return x; }
id(4); id(true);
```

```
4     : number
true  : boolean
id    : ∀T.T→T
```

polymorphic type

```
- richer types approximate behavior better
- depends on runtime representation of values
```

Types Example

```
if (a < 5) { 5 } else { "four" }
```

```
5      : number
"four" : string
if     : number|string
```

union type

```
- richer types approximate behavior better
- depends on runtime representation of values
```

Types Example

```
float distance = 12.0, time = 4.0
float velocity = time / distance
```

```
distance : float<m>
time     : float<s>
velocity : float<m/s>
```

unit-of-measure type

```
- no runtime problems, but not correct (v = d / t)
- types can enforce other correctness properties
```

What kind of types?

- Simple	`int`, `float→float`, `bool`
- Named	`class A`, `newtype Id`
- Polymorphic	`List<X>`, `∀a.a→a`
- Union/sum (one of)	`string|string[]`
- Unit-of-measure	`float<m>`, `float<m/s>`
- Structural	`{ x: number, y: number }`
- Intersection (all of)	`Comparable&Serializable`
- Recursive	`μT.int|T*T` (binary int tree)
- Ownership	`&mut data`
- Dependent – values in types	`Vector 3`
- ... many more ...	

Why types?

Why types?

- Statically prove the absence of certain (wrong) runtime behavior
  - “Well-typed programs cannot go wrong.” [Reynolds1985]
  - Also logical properties beyond runtime problems

What are types?

- Static classification of expressions by approximating the runtime values they may produce
- Richer types approximate runtime behavior better
- Richer types may encode correctness properties beyond runtime crashes

What is the difference between typing and testing?

- Typing is an over-approximation of runtime behavior (proof of absence)
- Testing is an under-approximation of runtime behavior (proof of presence)

Types and language design

Types influence language design

- Types abstract over implementation
  - Any value with the correct type is accepted
- Types enable separate or incremental compilation
  - As long as the public interface is implemented, dependent modules do not change

Can we have our cake and eat it too?

- Ever more precise types lead to ever more correct programs
- What would be the most precise type you can give?
  - The exact set of values computed for a given input?
- Expressive typing problems become hard to compute
- Many are undecidable, if they imply solving the halting problem
- Designing type systems always involves trade-offs

Relations between Types

Comparing Types

```
interface Point2D { x: number, y: number }
interface Vector2D { x: number, y: number }
var p1: Point2D = { x: 5, y: -11 }
var p2: Vector2D = p1
```

Is this program correct?

- No, if types are compared by name
- Yes, if types are compared based on structure

Comparing Types

```
interface Point2D { x: number, y: number }
interface Point3D { x: number, y: number, z: number }
var p1: Point3D = { x: 5, y: -11, z: 0 }
var p2: Point2D = p1
```

Is this program correct?

- No, if equal types are required
- Yes, if structural subtypes are allowed
- When is `T` a subtype of `U`?
    - When a value of type `T` can be used when a value of `U` is expected
- What about nominal subtypes?
    - `interface Point3D extends Point2D`

Combination example: generics and subtyping

```
class A {}
class B extends A {}

B[] bs = new B[1];
A[] as = bs;
as[0]  = new A();
B b    = bs[0];
```

subtyping on arrays & mutable updates is unsound

```
- unsound = under-approximation of runtime behavior
- feature combinations are not trivial
```

Comparing Types

```
int i = 12
float f = i
```

Is this program correct?

- No, floats and integers have different runtime representations
- Yes, possible by coercion
  - Coercion requires insertion of code to convert between representations
- How is this different than subtyping?
  - Subtyping says that the use of the unchanged value is safe

Type Relations

What kind of relations between types?

- Equality `T=T` – syntactic or structural
- Subtyping `T<:T` – nominal or structural
- Coercion – requires code insertion

Implementing a Type Checker with Rewrite Rules

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Compute Type of Expression

```
rules

  type-check :
    Mod(e) -> t
    where <type-check> e => t

  type-check :
    String(_) -> STRING()

  type-check :
    Int(_) -> INT()

  type-check :
    Plus(e1, e2) -> INT()
    where
      <type-check> e1 => INT();
      <type-check> e2 => INT()

  type-check :
    Times(e1, e2) -> INT()
    where
      <type-check> e1 => INT();
      <type-check> e2 => INT()
```

```
1 + 2 * 3
```

```
Mod(
  Plus(Int("1"),
       Times(Int("2"),
             Int("3")))
)
```

```
INT()
```

Compute Type of Variable?

```
rules

  type-check :
    Let([VarDec(x, e)], e_body) -> t
    where
      <type-check> e => t_e;
      <type-check> e_body => t

  type-check :
    Var(x) -> t // ???
```

```
let
  var x := 1
 in
   x + 1
end
```

```
Mod(
  Let(
    [VarDec("x", Int("1"))]
  , [Plus(Var("x"), Int("1"))]
  )
)
```

?

Type Checking Variable Bindings

```
rules

  type-check(|env) :
    Let([VarDec(x, e)], e_body) -> t
    where
      <type-check(|env)> e => t_e;
      <type-check(|[(x, t_e) | env])> e_body => t

  type-check(|env) :
    Var(x) -> t
    where
      <fetch(?(x, t))> env
```

```
let
  var x := 1
 in
   x + 1
end
```

```
Mod(
  Let(
    [VarDec("x", Int("1"))]
  , [Plus(Var("x"), Int("1"))]
  )
)
```

```
INT()
```

Store association between variable and type in type environment

Pass Environment to Sub-Expressions

```
rules

  type-check :
    Mod(e) -> t
    where <type-check(|[])> e => t

  type-check(|env) :
    String(_) -> STRING()

  type-check(|env) :
    Int(_) -> INT()

  type-check(|env) :
    Plus(e1, e2) -> INT()
    where
      <type-check(|env)> e1 => INT();
      <type-check(|env)> e2 => INT()

  type-check(|env) :
    Times(e1, e2) -> INT()
    where
      <type-check(|env)> e1 => INT();
      <type-check(|env)> e2 => INT()
```

```
let
  var x := 1
 in
   x + 1
end
```

```
Mod(
  Let(
    [VarDec("x", Int("1"))]
  , [Plus(Var("x"), Int("1"))]
  )
)
```

```
INT()
```

But what about?

Type checking ill-typed/named programs?

- add rules for ‘bad’ cases

More complicated name binding patterns?

- Hoisting of variables in JavaScript functions
- Mutually recursive bindings
- Possible approaches
  - Multiple traversals over program
  - Defer checking until entire scope is processed
  - …

Name Binding Complicates Type Checking

Intermezzo: Testing Static Analysis

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Testing Name Resolution

```
test outer name [[
   let type t = u
       type [[u]] = int
       var x: [[u]] := 0
   in
      x := 42 ;
      let type u = t
          var y: u := 0
      in
         y := 42
      end
end
]] resolve #2 to #1
```

```
test inner name [[
   let type t = u
       type u = int
       var x: u := 0
   in
      x := 42 ;
      let type [[u]] = t
          var y: [[u]] := 0
      in
         y := 42
      end
end
]] resolve #2 to #1
```

Testing Type Checking

```
test integer constant [[
   let type t = u
       type u = int
       var x: u := 0
   in
      x := 42 ;
      let type u = t
          var y: u := 0
      in
         y := [[42]]
      end
end
]] run get-type to INT()
```

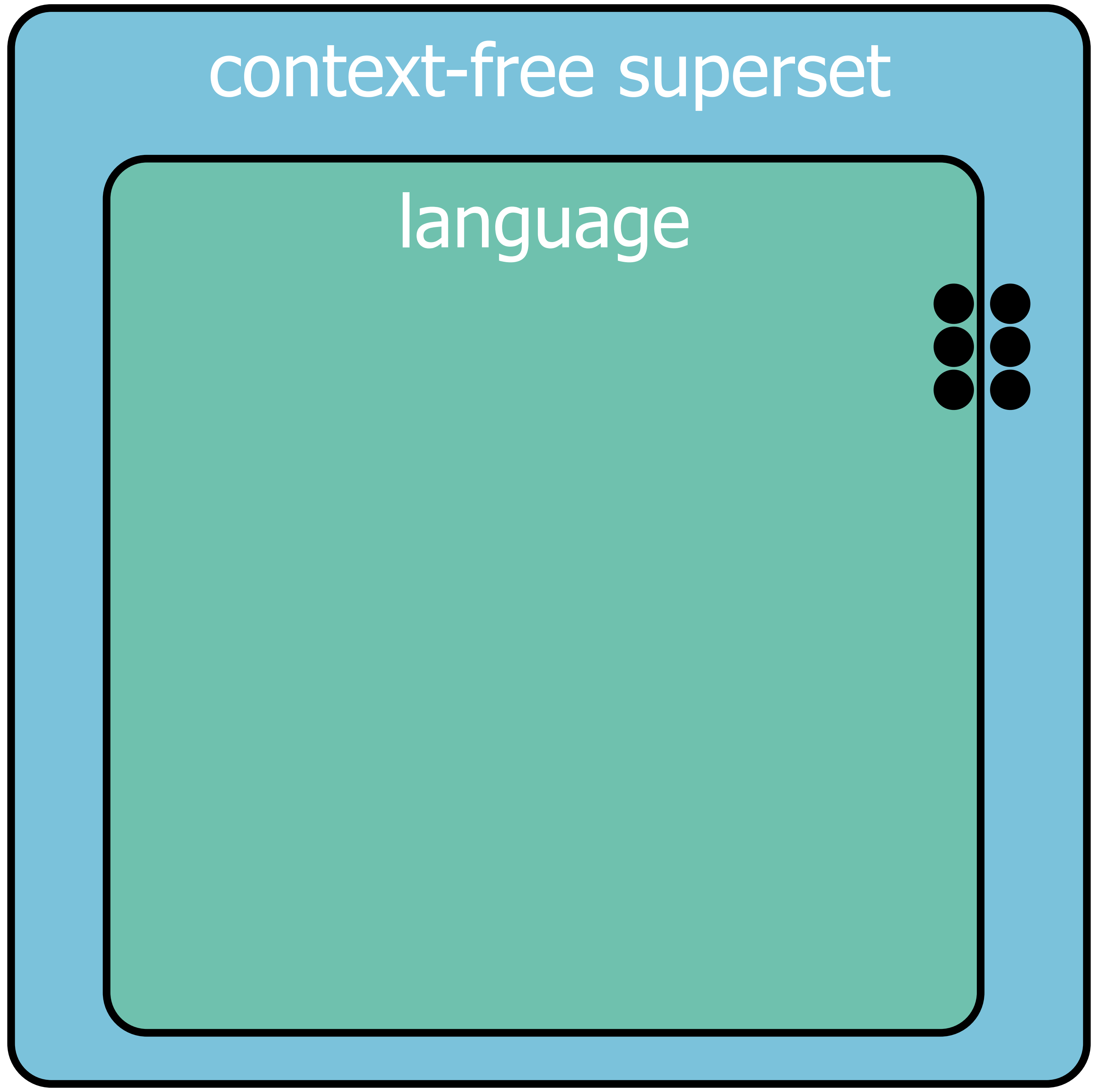
```
test variable reference [[
   let type t = u
       type u = int
       var x: u := 0
   in
      x := 42 ;
      let type u = t
          var y: u := 0
      in
         y := [[x]]
      end
end
]] run get-type to INT()
```

Testing Errors

```
test undefined variable [[
   let type t = u
       type u = int
       var x: u := 0
   in
      x := 42 ;
      let type u = t
          var y: u := 0
      in
         y := [[z]]
      end
end
]] 1 error
```

```
test type error [[
   let type t = u
       type u = string
       var x: u := 0
   in
      x := 42 ;
      let type u = t
          var y: u := 0
      in
         y := [[x]]
      end
end
]] 1 error
```

Test Corner Cases



Static Analysis for Tiger

Scope

```
let
  var x : int := 0 + z
  var y : int := x + 1
  var z : int := x + y + 1
 in
   x + y + z
end
```

Scope: Definition before Use

```
let
  var x : int := 0 + z  // z not in scope
  var y : int := x + 1
  var z : int := x + y + 1
 in
   x + y + z
end
```

Mutual Recursion

```
let
  function odd(x : int) : int =
    if x > 0 then even(x - 1) else false
  function even(x : int) : int =
    if x > 0 then odd(x - 1) else true
 in
   even(34)
end
```

```
let
  function odd(x : int) : int =
    if x > 0 then even(x - 1) else false
  var x : int
  function even(x : int) : int =
    if x > 0 then odd(x - 1) else true
 in
   even(34)
end
```

Mutually Recursive Functions should be Adjacent

```
let
  function odd(x : int) : int =
    if x > 0 then even(x - 1) else false
  function even(x : int) : int =
    if x > 0 then odd(x - 1) else true
 in
   even(34)
end
```

```
let
  function odd(x : int) : int =
    if x > 0 then even(x - 1) else false
  var x : int
  function even(x : int) : int =
    if x > 0 then odd(x - 1) else true
 in
   even(34)
end
```

Name Spaces

```
let
  type foo = int
  function foo(x : foo) : foo = 3
  var foo : foo := foo(4)
 in foo(56) + foo
end
```

Functions and Variables in Same Name Space

```
let
  type foo = int
  function foo(x : foo) : foo = 3
  var foo : foo := foo(4)
 in foo(56) + foo // both refer to the variable foo
end
```

Functions and variables are in the same namespace

Type Dependent Name Resolution

```
 let
   type point = {x : int, y : int}
   var origin : point := point { x = 1, y = 2 }
  in origin.x
end
```

Type Dependent Name Resolution

```
 let
   type point = {x : int, y : int}
   var origin : point := point { x = 1, y = 2 }
  in origin.x
end
```

`Resolving origin.x requires the type of origin`

Name Correspondence

```
let
  type point = {x : int, y : int}
  type errpoint = {x : int, x : int}
  var p : point
  var e : errpoint
 in
   p := point{ x = 3, y = 3, z = "a" }
   p := point{ x = 3 }
end
```

Name Set Correspondence

Duplicate Declaration of Field “x”

```
let
  type point = {x : int, y : int}
  type errpoint = {x : int, x : int}
  var p : point
  var e : errpoint
 in
   p := point{ x = 3, y = 3, z = "a" }
   p := point{ x = 3 }
end
```

Field “y” not initialized

Reference “z” not resolved

Recursive Types

```
let
  type intlist = {hd : int, tl : intlist}
  type tree = {key : int, children : treelist}
  type treelist = {hd : tree, tl : treelist}
  var l : intlist
  var t : tree
  var tl : treelist
 in
  l := intlist { hd = 3, tl = l };
  t := tree {
    key = 2,
    children = treelist {
      hd = tree{ key = 3, children = 3 },
      tl = treelist{ }
    }
  };
  t.children.hd.children := t.children
end
```

Recursive Types

```
let
  type intlist = {hd : int, tl : intlist}
  type tree = {key : int, children : treelist}
  type treelist = {hd : tree, tl : treelist}
  var l : intlist
  var t : tree
  var tl : treelist
 in
  l := intlist { hd = 3, tl = l };
  t := tree {
    key = 2,
    children = treelist {
      hd = tree{ key = 3, children = 3 },
      tl = treelist{ }
    }
  };
  t.children.hd.children := t.children
end
```

type mismatch

Field "tl" not initialized
Field "hd" not initialized