Refinement Types for TypeScript

Panagiotis Vekris Benjamin Cosman Ranjit Jhala

University of California, San Diego

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Extensible static analyses for modern scripting languages

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TypeScript

Wide scale

Looks like

Compiles to

JS

Extensible static analyses for modern scripting languages

TypeScript

Wide scale

Looks like JS

Compiles to JS

PL Interest

Higher Order Functions

Object Oriented

Optionally Typed

Generics

Extensible static analyses for modern scripting languages

```
class Greeter<T> {
    greeting: T;
    construct (property) Greeter<T>.greeting: T
        this.greeting = message;
    }
    greet() {
        return this.greeting;
    }
}
```

Verification

Documentation

No runtime overhead

Extensible static analyses for modern scripting languages

Fixed type tests

```
typeof x === 'string'

x === null
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assert (shape.tag & Circle)
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assert (user.auth())
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Extensible static analyses for modern scripting languages

Fixed type tests

```
typeof x === 'string'

x === null
```

+

User specified invariants

```
assert (shape.tag & Circle)

assert (user.auth())

assert (i < a.length)
```

Example

Compute the index of the minimum element of an array

```
function reduce(a, f, x) {
  var res = x;
  for (var i = 0; i < a.length; i++)
    res = f(res, a[i], i);
  return res;
}
```

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function reduce(a, f, x) {
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```

`reduce` folds over the elements of an array

```
function reduce(a, f, x) {
  var res = x;
  for (var i = 0; i < a.length; i++)
    res = f(res, a[i], i);
  return res;
}

function minIndex(a) {
  if (a.length <= 0) return -1;
  function step(min, cur, i) {
    return cur < a [ min ] ? i : min;
  }
  return reduce(a, step, 0);
}
```

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```

Calls `reduce` with an appropriate `step` function and initialization

Example

Compute the index of the minimum element of an array

Verification goal

Prove that all array accesses are within bounds

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function reduce(a, f, x) {
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Array bounds analysis:

$0 \leq \mathtt{min} < \mathtt{len}\ a$

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⇩

Constraint between **two values**

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function reduce(a, f, x) {
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Constraint between **value** and **closure**

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Constraint carries over through call to **function parameters**

Constraint between **value** and **closure**

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Constraint **checked** on invocation

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Problem

To check array access we must track **relations** between **closures** and **values**

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Solution

Refinement types

Refinement Types

$$\{\, \underbrace{v}_{\text{Value variable}} : \underbrace{b}_{\text{Base type}} \mid \underbrace{p}_{\text{Logical predicate}} \,\}$$

Refinement Types

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“Set of values v of type b such that formula p is true”

Refinement Types

$$\{\, v : b \mid p \,\}$$

Value variable

Base type

Logical predicate

"Set of values v of type b such that formula p is true"

E.g.: $\{\, v : \texttt{number} \mid 0 \leq v \wedge v < \texttt{len}\ a \,\}$

"Set of valid indexes for an array a"

How can we type `reduce`?

```
function reduce(a, f, x) { ... }
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TypeScript type

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function reduce<A,B>(a: A[], f: (B, A, number) => B, x: B): B { ... }
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Basic typing offers **some** guarantees

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Accepts Acc

Returns Acc

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TypeScript type

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function reduce<A,B>(a: A[], f: (B, A, number) => B, x: B): B { ... }
```

Does not capture:
"valid index of *a*"

Basic typing offers **some** guarantees
but **not value** related ones

How can we type `reduce` to account for valid indexes?

```
function reduce(a, f, x) { ... }
```

TypeScript type

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function reduce<A,B>(a: A[], f: (B, A, number) => B, x: B): B { ... }
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Refinement type

```
function reduce<A,B>(a: A[], f: (B, A, idx<a>) => B, x: B): B { ... }
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Refinement type

```
function reduce<A,B>(a: A[], f: (B, A, idx<a>) => B, x: B): B { ... }
```

```
type idx<a> = {v: number | 0 ≤ v ∧ v < len a}
```

How can we type `reduce` to account for valid indexes?

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function reduce(a, f, x) { ... }
```

TypeScript type

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function reduce<A,B>(a: A[], f: (B, A, number) => B, x: B): B { ... }
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Refinement type

```
function reduce<A,B>(a: A[], f: (B, A, idx<a>) => B, x: B): B { ... }
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Captures the relation between **closure** and **value**

Our contribution

Design a refinement type system for TypeScript

Challenges
Assignments `while (i < n) { i++; }`

Mutability
`var x = { f: 1 };`
`x.f = 2;`

Overloading
`foo(x: number): number`
`foo(x: boolean): boolean`

Annotation Overhead

Challenges	Solutions we used
Assignments `while (i < n) { i++; }`	SSA Transformation

Mutability
`var x = { f: 1 };`
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	Extend type system with immutability guarantees

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`foo(x: number): number`
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Annotation Overhead	Liquid Types

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Annotation Overhead	Liquid Types

Assignments

```
while (i < n) { i++; }
```

```
function reduce(a, f, x) {
  var r = x;
  for (var i = 0; i < a.length; i++)
    r = f(r, a[i], i);
  return r;
}
```

```diff
function reduce(a, f, x) {
  var r = x;
- for (var i = 0; i < a.length; i++)
-   r = f(r, a[i], i);
  return r;
}
```

```diff
function reduce(a, f, x) {
  var r = x;
+ var i = 0;
+ while (i < a.length) {
+   r = f(r, a[i], i);
+   i = i + 1;
+ }
  return r;
}
```

What is the type of `i`?

```
function reduce(a, f, x) {
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Types for `i`

{ number | v = 0 }

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        i = i + 1;
    } // i
    return r;
}
```

Types for `i`

{ number | v = 0 }

{ number | 0 ≤ v ≤ len a }

{ number | v = i + 1 }

{ number | v = len a }

No single type for `i`

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Types for `i`

{ number | v = 0 }

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{ number | v = i + 1 }

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Use different versions of `i`

```
function reduce(a, f, x) {
    var r = x;
    var i1 = 0;
    while (i2 < a.length) {
        r = f(r, a[i2], i2);
        i3 = i2 + 1;
    } // i4
    return r;
}
```

Types for i_1-i_4

i_1: { number | $v = 0$ }

i_2: { number | $0 \le v \le$ len a }

i_3: { number | $v = i_2 + 1$ }

i_1: { number | $v =$ len a }

Each version of `i` has a single precise type & gets assigned once

```
function reduce(a, f, x) {
    var r = x;
    var i₁ = 0;
    while (i₂ < a.length) {
        r = f(r, a[i₂], i₂);
        i₃ = i₂ + 1;
    } // i₄
    return r;
}
```

Types for i_1-i_4

i_1: { number | $v = 0$ }
i_2: { number | $0 \leq v \leq \text{len } a$ }
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Static Single Assignment (SSA)

```
function reduce(a, f, x) {
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    while (i₂ < a.length) {
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i_1: { number | $v = 0$ }
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Types for i_1-i_4

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i_2: { number | $0 \leq v \leq \mathrm{len}\ a$ }

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How do we check these types?

Reminder

Assignment

`x = e`

generates subtyping constraint

`Type(e) <: Type(x)`

Subtyping Constraints

```
function reduce(a, f, x) {
    var r = x;
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    while (i₂ < a.length) {
        r = f(r, a[i₂], i₂);
        i₃ = i₂ + 1;
    } // i₄
    return r;
}
```

Generated constraints

$\text{Type}(0) \quad <: \quad \text{Type}(i_1)$

Subtyping Constraints

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```

i: loop induction variable

$i_2 = \phi(i_1, i_3)$

Generated constraints

Type(0) <: Type(i_1)

Subtyping Constraints

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Generated constraints

Type(0)	<:	Type(i_1)
Type(i_1)	<:	Type(i_2)

Subtyping Constraints

```
function reduce(a, f, x) {
    var r = x;
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    while (i₂ < a.length) {
        r = f(r, a[i₂], i₂);
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}
```

i: loop induction variable

$$i_2 = \phi(i_1, i_3)$$

Generated constraints

	Type(0)	<:	$\mathrm{Type}(i_1)$
	$\mathrm{Type}(i_1)$	<:	$\mathrm{Type}(i_2)$
loop_cond ⊢	$\mathrm{Type}(i_3)$	<:	$\mathrm{Type}(i_2)$

Subtyping Constraints

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$i_2 = \phi(i_1, i_3)$

Loop condition

$i_2 < \mathrm{len}\ a$

Generated constraints

$\mathrm{Type}(0) <: \mathrm{Type}(i_1)$

$\mathrm{Type}(i_1) <: \mathrm{Type}(i_2)$

$\mathrm{loop\_cond} \vdash \mathrm{Type}(i_3) <: \mathrm{Type}(i_2)$

Path Sensitivity

Subtyping Constraints

```
function reduce(a, f, x) {
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}
```

Loop condition

$i_2 < \mathrm{len}\; a$

Generated constraints

$$\mathrm{Type}(0) <: \mathrm{Type}(i_1)$$
$$\mathrm{Type}(i_1) <: \mathrm{Type}(i_2)$$
$$\mathrm{loop\_cond} \vdash \mathrm{Type}(i_3) <: \mathrm{Type}(i_2)$$
$$\mathrm{loop\_cond} \vdash \mathrm{Type}(i_2 + 1) <: \mathrm{Type}(i_3)$$

Subtyping Constraints

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Safe Array Access

Loop condition

$i_2 < \mathrm{len}\ a$

Generated constraints

$$\mathrm{Type}(0) <: \mathrm{Type}(i_1)$$

$$\mathrm{Type}(i_1) <: \mathrm{Type}(i_2)$$

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$$\mathrm{loop\_cond} \vdash \mathrm{Type}(i_2 + 1) <: \mathrm{Type}(i_3)$$

$$\mathrm{loop\_cond} \vdash \mathrm{Type}(i_2) <: \mathrm{idx}\langle a \rangle$$

Subtyping Constraints

i_1: { number | v = 0 }
i_2: { number | 0 ≤ v ≤ len a }
i_3: { number | v = i_2 + 1 }
i_4: { number | v = len a }

Loop condition

i_2 < len a

Substitute

Generated constraints

	Type(0)	<:	Type(i_1)
	Type(i_1)	<:	Type(i_2)
loop_cond ⊢	Type(i_3)	<:	Type(i_2)
loop_cond ⊢	Type(i_2 + 1)	<:	Type(i_3)
loop_cond ⊢	Type(i_2)	<:	idx<a>

Subtyping Constraints

After substitution

$$\{\, num \mid v = 0 \,\} <: \{\, num \mid v = 0 \,\}$$

$$\{\, num \mid v = 0 \,\} <: \{\, num \mid 0 \leq v \leq \mathtt{len}\ a \,\}$$

$$i_2 < \mathtt{len}\ a \vdash \{\, num \mid v = i_2 + 1 \,\} <: \{\, num \mid 0 \leq v \leq \mathtt{len}\ a \,\}$$

$$i_2 < \mathtt{len}\ a \vdash \{\, num \mid v = i_2 + 1 \,\} <: \{\, num \mid v = i_2 + 1 \,\}$$

$$i_2 < \mathtt{len}\ a \vdash \{\, num \mid 0 \leq v \leq \mathtt{len}\ a \,\} <: \{\, num \mid 0 \leq v < \mathtt{len}\ a \,\}$$

Subtyping Constraints

Convert to logical implications

$$
\begin{array}{rcrcr}
 & & v = 0 & \Rightarrow & v = 0 \\
 & & v = 0 & \Rightarrow & 0 \leq v \leq \mathtt{len}\ a \\
i_2 < \mathtt{len}\ a & \Rightarrow & v = i_2 + 1 & \Rightarrow & 0 \leq v \leq \mathtt{len}\ a \\
i_2 < \mathtt{len}\ a & \Rightarrow & v = i_2 + 1 & \Rightarrow & v = i_2 + 1 \\
i_2 < \mathtt{len}\ a & \Rightarrow & 0 \leq v \leq \mathtt{len}\ a & \Rightarrow & 0 \leq v < \mathtt{len}\ a
\end{array}
$$

Subtyping Constraints

Convert to logical implications

Solved via SMT

$$
\begin{array}{rcrcr}
 & & v = 0 & \Rightarrow & v = 0 \\
 & & v = 0 & \Rightarrow & 0 \leq v \leq \mathtt{len}\ a \\
i_2 < \mathtt{len}\ a & \Rightarrow & v = i_2 + 1 & \Rightarrow & 0 \leq v \leq \mathtt{len}\ a \\
i_2 < \mathtt{len}\ a & \Rightarrow & v = i_2 + 1 & \Rightarrow & v = i_2 + 1 \\
i_2 < \mathtt{len}\ a & \Rightarrow & 0 \leq v \leq \mathtt{len}\ a & \Rightarrow & 0 \leq v < \mathtt{len}\ a
\end{array}
$$

Challenges	Solutions we used
Assignments `while (i < n) { i++; }`	SSA Transformation

Mutability
`var x = { f: 1 };`
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	Extend type system with immutability guarantees

Overloading
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Annotation Overhead	Liquid Types

Mutability

```
var x = { f: 1 };
x.f = 2;
```

Why is the access `a[i]` safe?

```
function reduce(a, f, x) {
  var res = x;
  for (var i = 0; i < a.length; i++)
    res = f(res, a[i], i);
  return res;
}
```

Why is the access `a[i]` safe?

```
function reduce(a, f, x) {
  var res = x; 1
  for (var i = 0; i < a.length; i++)
    res = f(res, a[i], i);
  return res;
}
```

1. `i` is initialized to `0`

Why is the access `a[i]` safe?

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1. `i` is initialized to `0`
2. `i` is bounded by `a`'s length

Why is the access `a[i]` safe?

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function reduce(a, f, x) {
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  return res;
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1 2 3

1. `i` is initialized to `0`
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3. `i` increases only

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```

1. `i` is initialized to `0`
2. `i` is bounded by `a`'s length
3. `i` increases only
4. **Length of `a` does not mutate** in loop

What if array’s length mutates in loop?

```
function reduce(a, f, x) {
  var res = x;
  for (var i = 0; i < a.length; i++) {
    a.pop();
    res = f(res, a[i], i);
  }
  return res;
}
```

lib.d.ts

```
interface Array<T> {
  /**
   *  Removes the last element from an array and returns it.
   */
  pop(): T;
}
```

What if array's length mutates in loop?

Silently updates `a.length`

```
function reduce(a, f, x) {
  var res = x;
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What if array's length mutates in loop?

Check becomes stale

Silently updates a.length

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    res = f(res, a[i], i);
  }
  return res;
}
```

Silently updates a.length

Unsafe access!

```
interface Array<T> {
  /**
   *  Removes the last element from an array and returns it.
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  pop(): T:
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lib.d.ts

Problem: stale checks break value reasoning

Check becomes stale

Silently updates a.length

```
function reduce(a, f, x) {
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Unsafe access!

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Extend type system to enforce immutability constraints

Literature in Object & Reference Immutability

M. Tschantz and M. D. Ernst. Javari: Adding reference immutability to Java. OOPSLA, 2005.

Y. Zibin, A. Potanin, M. Ali, S. Artzi, A. Kiezun, and M. D. Ernst. Object and Reference Immutability using Java Generics. ESEC/FSE, 2007.

Y. Zibin, A. Potanin, P. Li, M. Ali, and M. D. Ernst. Ownership and Immutability in Generic Java. OOPSLA, 2010.

C. S. Gordon, M. J. Parkinson, J. Parsons, A. Bromfield, and J. Duffy. Uniqueness & Reference Immutability for Safe Parallelism. OOPSLA, 2012.

C. S. Gordon, M. D. Ernst, and D. Grossman. Rely-Guarantee References for Refinement Types over Aliased Mutable Data. PLDI, 2013.

F. Militão, J. Aldrich, and L. Caires. Rely-Guarantee Protocols. ECOOP, 2014.

Literature in Object & Reference Immutability

Y. Zibin, A. Potanin, M. Ali, S. Artzi, A. Kiezun, and M. D. Ernst. Object and Reference Immutability using Java Generics. ESEC/FSE, 2007.

- ✓ Simple extension to type system
- ✓ Encoded in base types – refinements leverage immutability guarantees

Immutability Generic Java [Zibin'07]

```
function reduce<A,B>(a: Array<Immutable,A>,
                     f: (B,A,idx<a>) => B,
                     x: B): B {
  var res = x;
  for (let i = 0; i < a.length; i++)
    res = f(res, a[i], i);
  return res;
}
```

Mutability as type parameter

Immutability Generic Java [Zibin'07]

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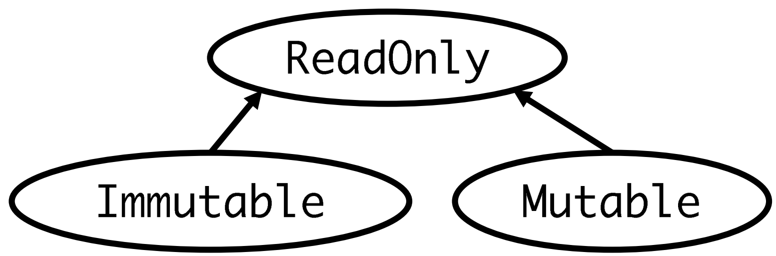
Mutability as type parameter



	This can mutate?	Others can mutate?
ReadOnly	✗	✓
Mutable	✓	✓
Immutable	✗	✗

Immutability Generic Java [Zibin'07]

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function reduce<A,B>(a: Array<Immutable,A>,
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  return res;
}
```
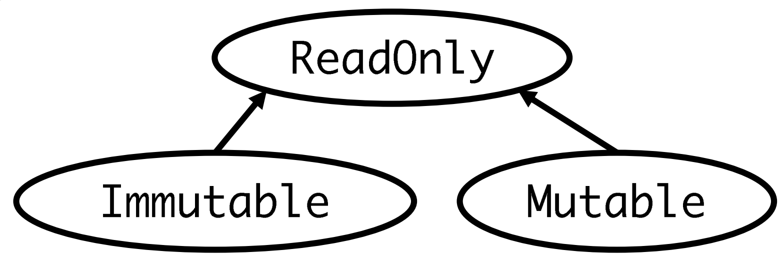

Mutability as type parameter

Only immutable portions in refinement



	This can mutate?	Others can mutate?
ReadOnly	✗	✓
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Immutable	✗	✗

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    res = f(res, a[i], i);
  }
  return res;
}
```

lib-IGJ.d.ts

```
interface Array<M extends ReadOnly, T> {
  /**
   * Removes the last element from an array and returns it.
   */
  /*@ Mutable */ pop(): T;
}
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Immutability Generic Java [Zibin'07]

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function reduce<A,B>(a: Array<Immutable,A>,
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    res = f(res, a[i], i);
  }
  return res;
}
```

Call to pop is flagged as an error, because pop may only be applied to Mutable receivers

lib-IGJ.d.ts

```
interface Array<M extends ReadOnly, T> {
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   * Removes the last element from an array and returns it.
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```

Challenges	Solutions we used
Assignments `while (i < n) { i++; }`	SSA Transformation

Mutability
`var x = { f: 1 };`
`x.f = 2;`
	Extend type system with immutability guarantees

Overloading
`foo(x: number): number`
`foo(x: boolean): boolean`
	Two-phased typing

Annotation Overhead	Liquid Types

Value Based

Overloading

```
foo(x: number): number
foo(x: boolean): boolean
```

Value Based Overloading

Function reflects upon and behaves according to types of its arguments

Value Based Overloading

Function reflects upon and behaves according to types of its arguments

```
function $reduce(a, f, x?) {
  if (arguments.length === 3)
    return reduce(a, f, x);
  else
    return reduce(a.slice(1), f, a[0]);
}
```

#args	Signature
2	
3	

Value Based Overloading

Function reflects upon and behaves according to types of its arguments

```
function $reduce(a, f, x?) {
  if (arguments.length === 3)
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    return reduce(a.slice(1), f, a[0]);
}
```

1st behavior – 3 args:
x is of type B

#args	Signature
2	
3	`<A,B>(a: A[] , f: (B,A,idx<a>) => B, x: B): B`

Value Based Overloading

Function reflects upon and behaves according to types of its arguments

```
function $reduce(a, f, x?) {
  if (arguments.length === 3)
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    return reduce(a.slice(1), f, a[0]);
}
```

2nd behavior – 2 args:
x is of type
undefined

#args	Signature
2	`<A> (a: A[]⁺, f: (A,A,idx<a>) => A ): A`
3	`<A,B>(a: A[] , f: (B,A,idx<a>) => B, x: B): B`

Value Based Overloading

Function reflects upon and behaves according to types of its arguments

Q1: What makes it challenging?

Q2: How pervasive is it?

Q1: What makes it challenging?

```
function $reduce(a, f, x?) {
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```

Type Analysis (base types)	Value Analysis (refinements)

Q1: What makes it challenging?

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function $reduce(a, f, x?) {
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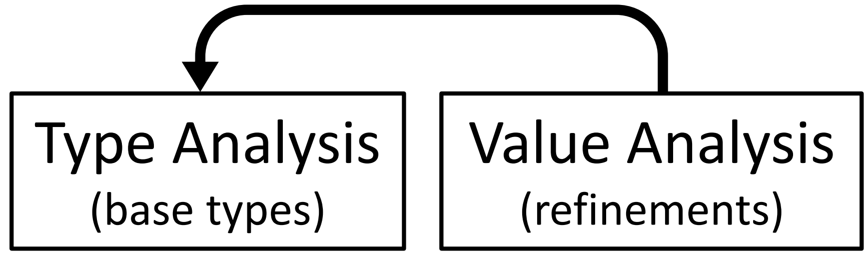

Refinements use invariants established by base types

E.g. tracking the `.length` access requires `arguments` to be array

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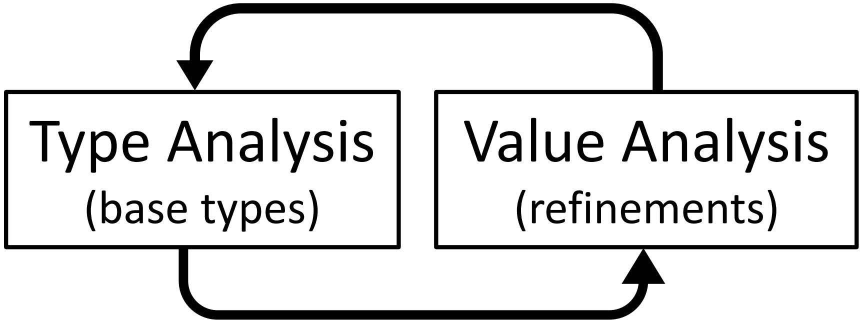

Refinements use invariants established by base types

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Type reasoning requires tracking logical relationships

E.g. base type of `x` depends on the value of `arguments.length`

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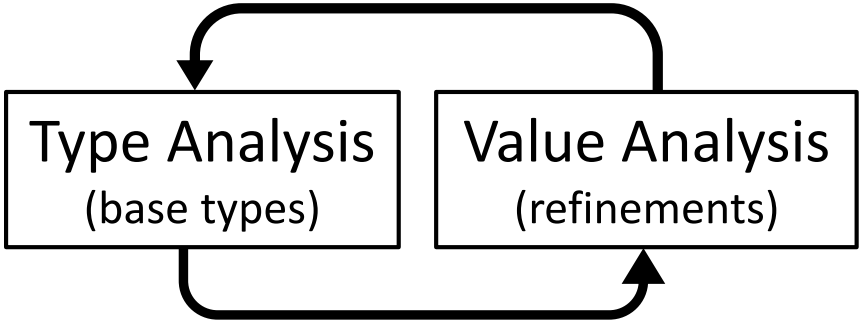


Refinements use invariants established by base types

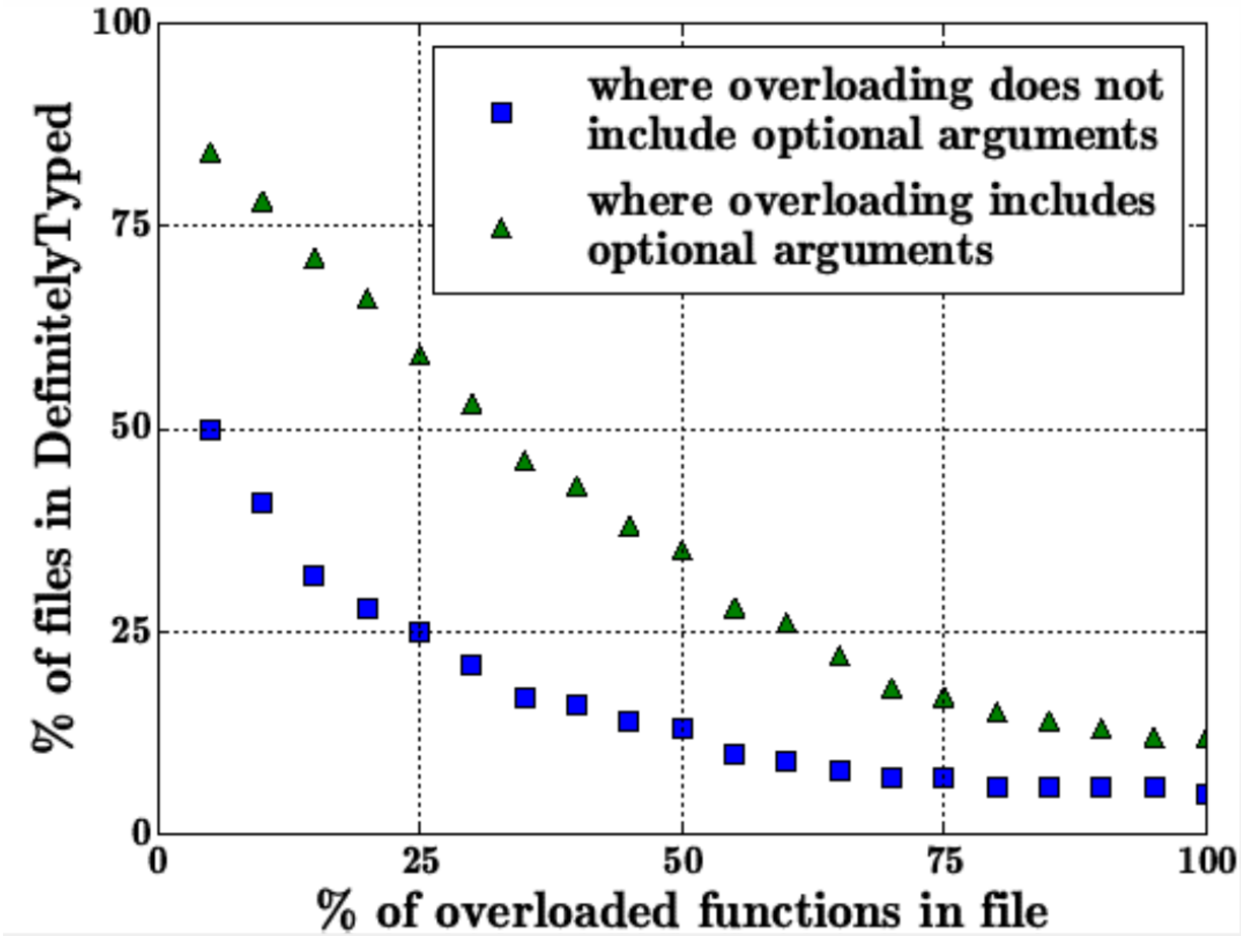
E.g. tracking the `.length` access requires `arguments` to be array

Type reasoning requires tracking logical relationships

E.g. base type of `x` depends on the value of `arguments.length`

Circular dependency complicates **formal reasoning** & **implementation**

Q2: How pervasive is it?

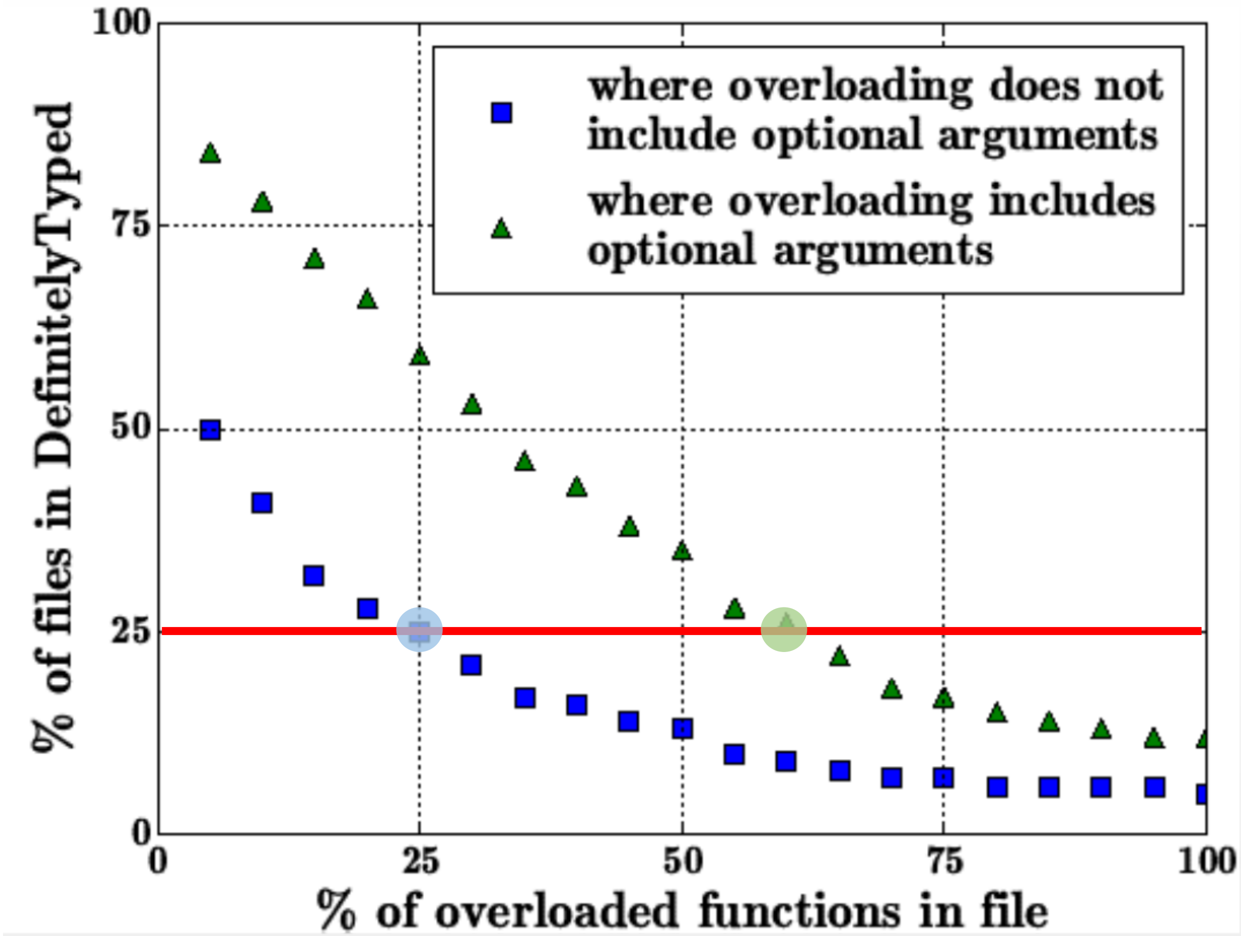


Study set:

DefinitelyTyped: The repository for high quality TypeScript type definitions

`http://definitelytyped.org/`

Q2: How pervasive is it?



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How do we check overloaded functions?

Two-Phased Typing [ECOOP'15]

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Phase 1a. Make clones of body for each overload

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Phase 1b. Check body under clone signature

How do we check overloaded functions?

Two-Phased Typing [ECOOP'15]

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function $reduce#1<A>(a: A[]⁺, f: (A,A,idx<a>) => A): A {
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}
```

Error: expecting type A, passed x of type undefined

Value- and path-insensitive type-checking

Phase 1b. Check body under clone signature

How do we check overloaded functions?

Two-Phased Typing [ECOOP’15]

```
function $reduce#1<A>(a: A[]+, f: (A,A,idx<a>) => A): A {
  if (arguments.length === 3)
    return assert(false);
  else
    return reduce(a.slice(1), f, a[0]);
}
```

Replace errors with `assert(false)`, trusting they are indeed dead-code

Phase 1b. Check body under clone signature

How do we check overloaded functions?

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Prove dead-code with flow- and path-sensitive analysis

Phase 2. Refinement Type Checking

How do we check overloaded functions?

Two-Phased Typing [ECOOP'15]

Signature implies: `arguments.length = 2`

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Condition makes branch's environment inconsistent

Prove dead-code with flow- and path-sensitive analysis

Phase 2. Refinement Type Checking

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Phase 2. Refinement Type Checking

Also in the paper…

Scaling to TypeScript

- Type features

  Object literal types
  Interface types
  Primitive types
  Unsound features
  Undefined & null types
  Co- & Contra-variant subtyping
  Unchecked overloads
  `any` *type*

- Array support

- Flexible object initialization

  Internal: Constructors
  External: Unique references

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  Internal: Constructors
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Formal Results

Refinement type safety for core language

Experimental Evaluation

Benchmark suite

File	LOC
`navier-stokes`	366
`splay`	206
`richards`	304
`raytrace`	576
`transducers`	588
`d3-arrays`	189
`tsc-checker`	293
Total	**2522**

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Octane
- NavierStokes: 2D fluid motion simulator
- Splay: splay tree implementation
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Composable algorithmic transformations

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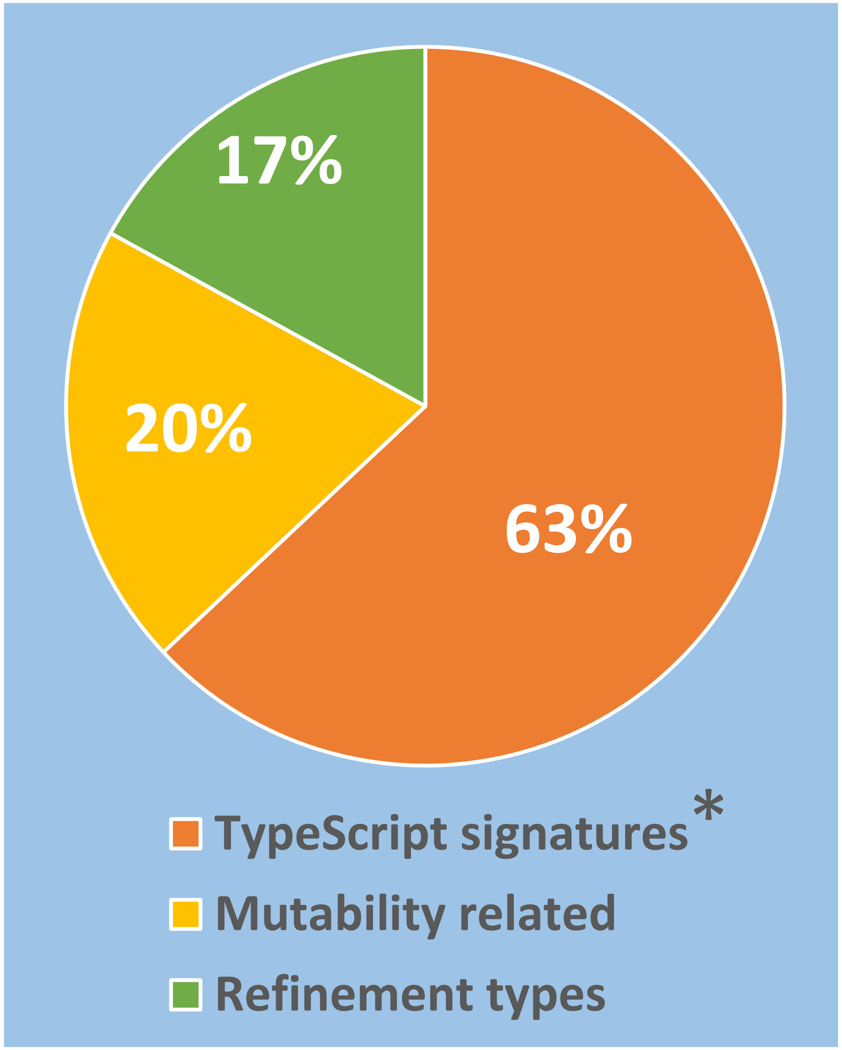
- Array operations

Microsoft's TypeScript compiler

- Parts of `core.ts` and `checker.ts`

Annotation Overhead

File	LOC	Annots (% LOC)
navier-stokes	366	24.6
splay	206	9.7
richards	304	27.3
raytrace	576	14.6
transducers	588	27.6
d3-arrays	189	26.5
tsc-checker	293	23.4
Total	**2522**	**21.4**



* Programs need to be fully typed
– no any type in signatures

Performance

File	LOC	Annots (% LOC)	Time (sec)
`navier-stokes`	366	24.6	473
`splay`	206	9.7	6
`richards`	304	27.3	7
`raytrace`	576	14.6	15
`transducers`	588	27.6	12
`d3-arrays`	189	26.5	37
`tsc-checker`	293	23.4	62
Total	**2522**	**21.4**	

Performance

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Total	**2522**	**21.4**	

More than 100 static array access sites with dynamically computed indexes

Properties Tested

- Property accesses
- Array bounds checks
- Overloads
- Safe Downcasts
  - Class based
  - Ad hoc type hierarchies
- User specified value properties. E.g. a function:
  - returns a positive number
  - accepts non-empty arrays

Properties Tested

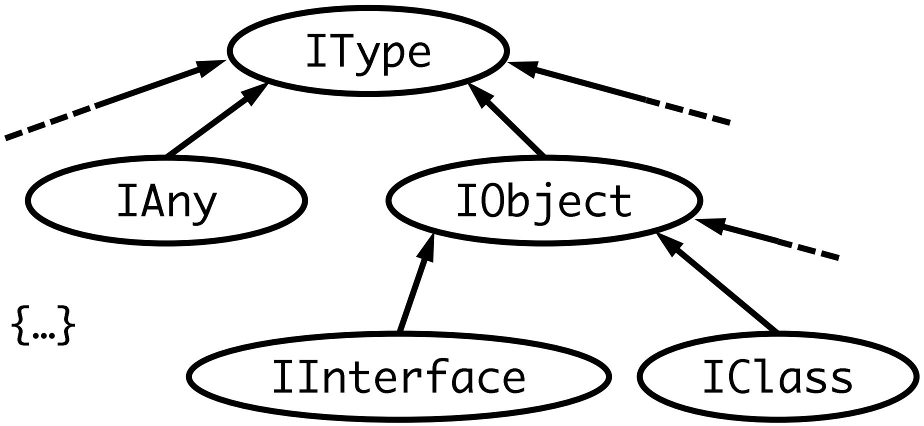
Safe Downcasts

Ad hoc type hierarchies

Example taken from:

`TypeScript compiler - v1.0.1.0 - src/compiler/types.ts`

```
interface IType {…}
interface IClass extends IType {…}
interface IAny extends IType {…}
interface IObject extends IType {…}
interface IInterface extends IObject {…}
```



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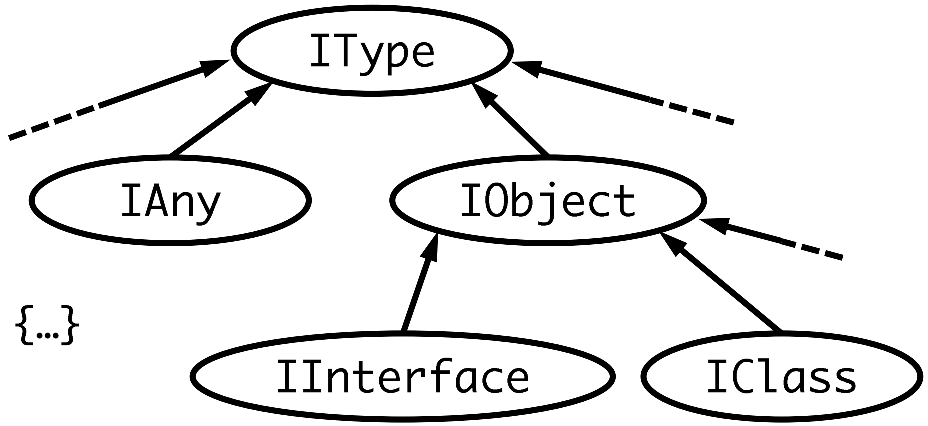
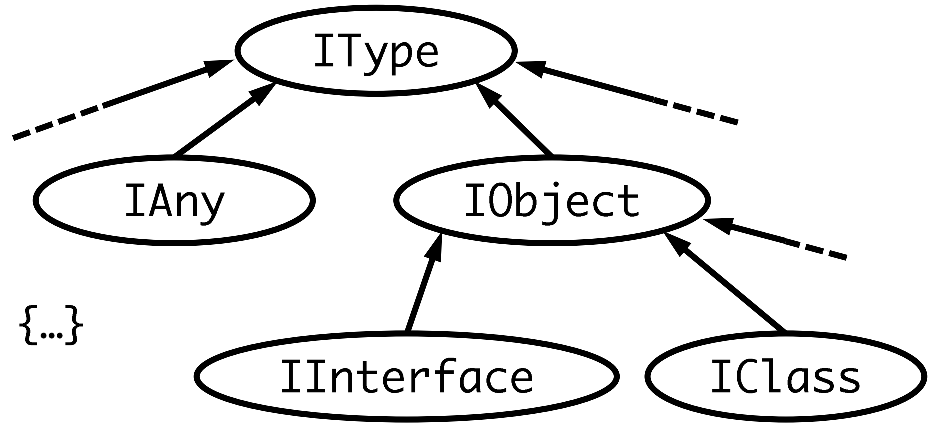


TypeScript interfaces are plain JavaScript objects

no type information at runtime

```
interface IType { flags:TypeFlags; }
interface IClass extends IType {…}
interface IAny extends IType {…}
interface IObject extends IType {…}
interface IInterface extends IObject {…}
```




```
const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```

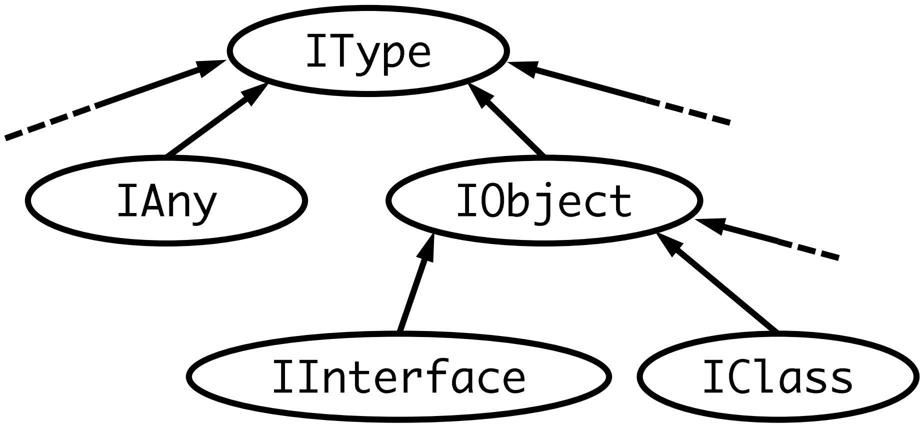
TypeScript interfaces are plain JavaScript objects

no type information at runtime

Explicit field (`flags`) to encode type info

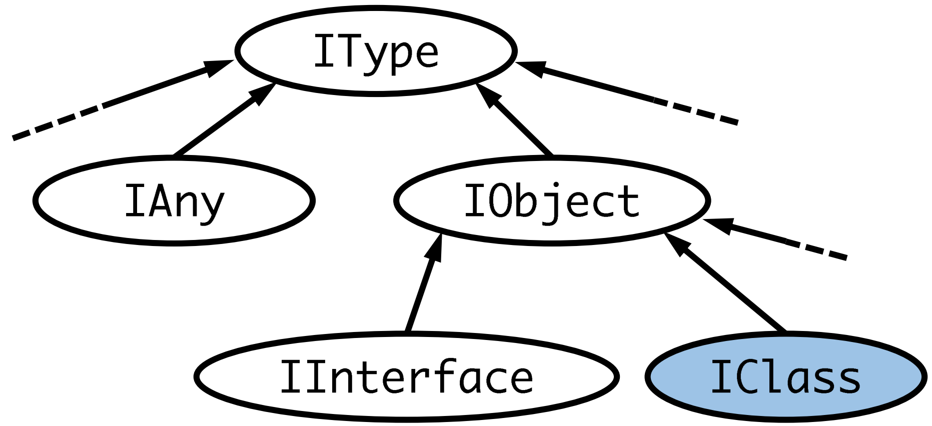
needed for dynamic tests

```
interface IType { flags:TypeFlags; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```



Invariants

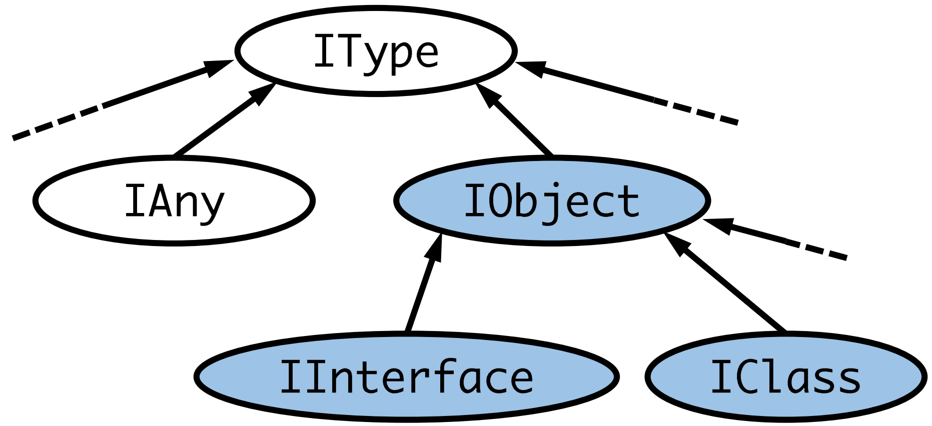
```
interface IType { flags:TypeFlags; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```



Invariants

t.flags & 0x0400 ≠ 0 ⇒ t: IClass

```
interface IType { flags:TypeFlags; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```



Invariants

$$\texttt{t.flags \& 0x0400} \neq 0 \Rightarrow \texttt{t: IClass}$$

$$\texttt{t.flags \& (0x0400|0x0800|...)} \neq 0 \Rightarrow \texttt{t: IObject}$$

...

```
interface IType { flags:TypeFlags; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```

Problem

Unchecked invariants

```
t.flags & 0x0400                 ≠ 0 ⇒ t: IClass

t.flags & (0x0400|0x0800|…) ≠ 0 ⇒ t: IObject

...
```

```
interface IType { flags:TypeFlags; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```

```
var t: IType = …
if (t.flags & TypeFlags.Class) {
  var o = <IClass> t;
}
```

Problem

Unchecked invariants

```
t.flags & 0x0400              ≠ 0 ⇒ t: IClass
t.flags & (0x0400|0x0800|…) ≠ 0 ⇒ t: IObject
                ...
```

```
interface IType { flags:TypeFlags; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```

```
var t: IType = …
if (t.flags & TypeFlags.Class) {
  var o = <IClass> t;
}
```

Problem

Unchecked invariants

```
t.flags & 0x0400              ≠ 0 ⇒ t: IClass
t.flags & (0x0400|0x0800|…) ≠ 0 ⇒ t: IObject
...
```

```
interface IType { flags:TypeFlags; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```

```
var t: IType = …
if (t.flags & TypeFlags.Class) {
  var o = <IAny> t;
}
```

No static or dynamic error

Problem

Unchecked invariants

$$\texttt{t.flags \& 0x0400} \neq 0 \Rightarrow \texttt{t: IClass}$$

$$\texttt{t.flags \& (0x0400|0x0800|…)} \neq 0 \Rightarrow \texttt{t: IObject}$$

...

```
interface IType { flags:TypeFlags; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```

```
var t: IType = …
if (t.flags & TypeFlags.Class) {
  var o = <IAny> t;
}
```

No static or dynamic error

Problem

Unchecked invariants

Solution

Encode invariants in refinement types

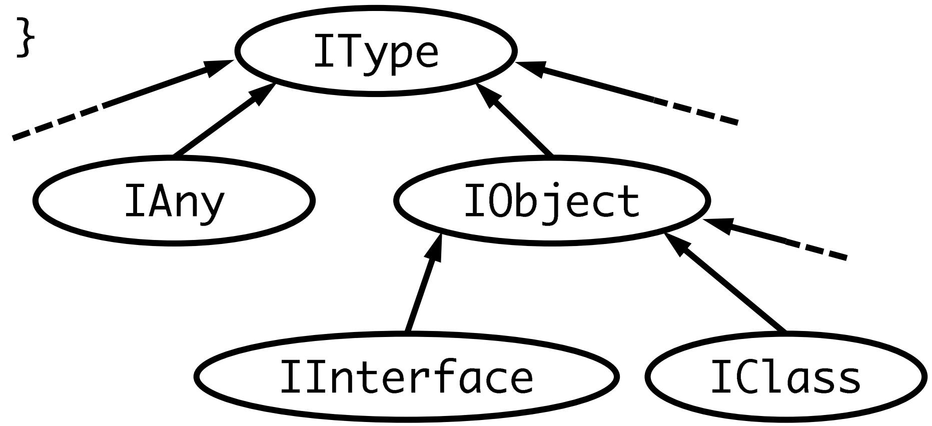
Encode type information in logic

```
interface S {…}
```

$\Downarrow$

```
x: S ⇔ implements(x, 'S')
```

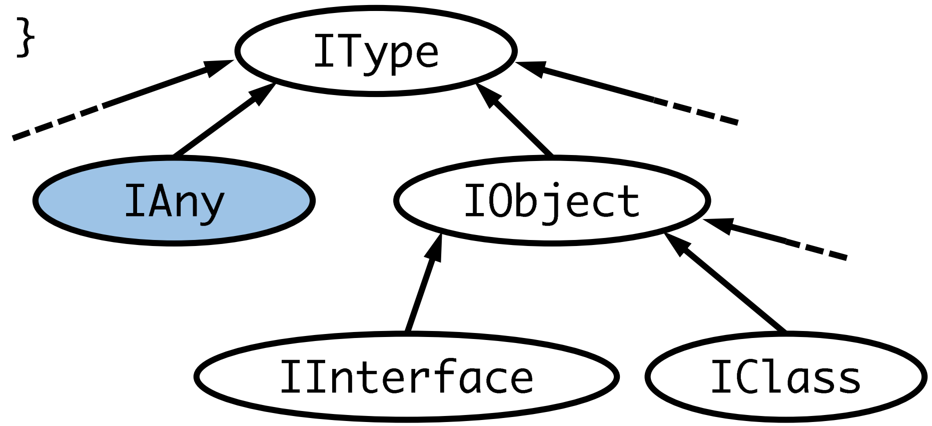
```
interface IType { flags:TypeFlagInv; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```



Type for `flags` accounts for possible sub-interfaces

```
type TypeFlagInv  =   TypeFlags
```

```
interface IType { flags:TypeFlagInv; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
            | Interface
            | ...
}
```



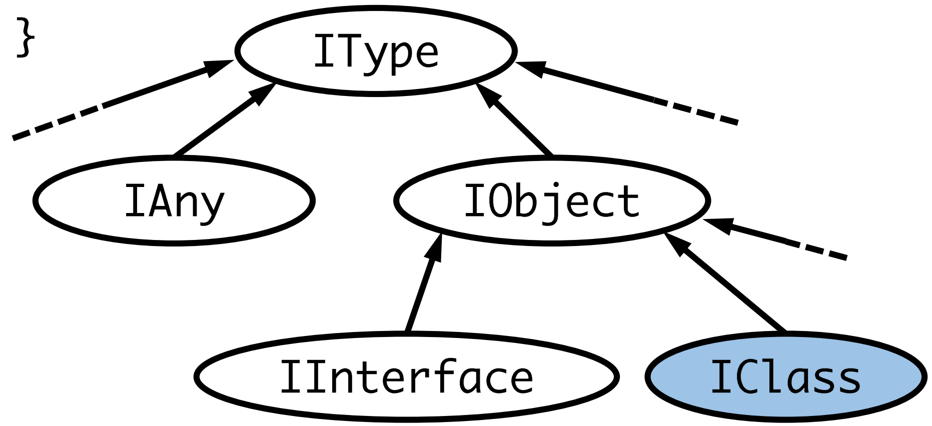
Type for `flags` accounts for possible sub-interfaces

```
type TypeFlagInv  = { TypeFlags |
    mask(v,0x0001) ⇒ implements(this, 'IAny')
}
```

Bitwise AND

The containing object

```
interface IType { flags:TypeFlagInv; }
...

const enum TypeFlags {
   Any       = 0x0001,
   Class     = 0x0400,
   Interface = 0x0800,
   ObjType   = Class
             | Interface
             | ...
}
```



Type for `flags` accounts for possible sub-interfaces

```
type TypeFlagInv  = { TypeFlags |
    mask(v,0x0001) ⇒ implements(this, 'IAny')
  ∧ mask(v,0x0400) ⇒ implements(this, 'IClass')

}
```

```
interface IType { flags:TypeFlagInv; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
  Interface = 0x0800,
  ObjType   = Class
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            | ...
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type TypeFlagInv  = { TypeFlags |
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  ∧ mask(v,0x0400) ⇒ implements(this, 'IClass')
  ∧ mask(v,0x0800) ⇒ implements(this, 'IInterface')
  ∧ … }
```

```
interface IType { flags:TypeFlagInv; }
...

const enum TypeFlags {
  Any       = 0x0001,
  Class     = 0x0400,
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  ObjType   = Class
            | Interface
            | ...
}
```

```
var t: IType = …
if (t.flags & TypeFlags.Class) {
  var o = <IClass> t;
}
```

```
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    mask(v,0x0001) ⇒ implements(this, 'IAny')
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interface IType { flags:TypeFlagInv; }
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            | ...
}
```

```
var t: IType = …
if (t.flags & TypeFlags.Class) {
  var o = <IClass> t;
}
```

Check downcast

```
type TypeFlagInv  = { TypeFlags |
    mask(v,0x0001) ⇒ implements(this, 'IAny')
  ∧ mask(v,0x0400) ⇒ implements(this, 'IClass')
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```
var t: IType = …
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```

Check downcast

Invariant for
IType

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type TypeFlagInv  = { TypeFlags |
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            | ...
}
```

```
var t: IType = …
if (t.flags & TypeFlags.Class) {
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}
```

Check downcast

Invariant for IType	∧	Path condition: t.flags & 0x0400 ≠ 0

```
type TypeFlagInv  = { TypeFlags |
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const enum TypeFlags {
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var t: IType = …
if (t.flags & TypeFlags.Class) {
  var o = <IClass> t;
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Check downcast

Invariant for IType	∧	Path condition: t.flags & 0x0400 ≠ 0	⇒	implements(t, 'IClass')

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     mask(v,0x0001) ⇒ implements(this, 'IAny')
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var t: IType = …
if (t.flags & TypeFlags.Class) {
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Encode type information in logic

Check downcast

Invariant for IType	∧	Path condition: t.flags & 0x0400 ≠ 0	⇒	t: IClass

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type TypeFlagInv  = { TypeFlags |
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var t: IType = …
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```

Encode type information in logic

Check downcast

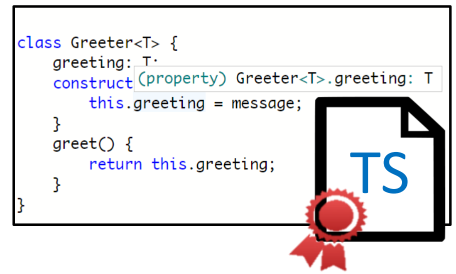
Invariant for IType	∧	Path condition: $t.flags \,\&\, 0x0400 \neq 0$	⇒	t: IClass

```
type TypeFlagInv  = { TypeFlags |
    mask(v,0x0001) ⇒ implements(this, 'IAny')
  ∧ mask(v,0x0400) ⇒ implements(this, 'IClass')
  ∧ mask(v,0x0800) ⇒ implements(this, 'IInterface')
  ∧ … }
```

Refinement Types for TypeScript

Extensible static analysis for a modern scripting language

- ✓ Fixed type tests
- ✓ User specified invariants



Challenges	Solutions
Assignments	SSA Transformation
Mutability	Extend type system with immutability guarantees
Overloading	Two-phased typing
Annotation Overhead	Liquid Types

Source: `github.com/UCSD-PL/refscript`

Demo: `goto.ucsd.edu/~pvekris/refscript`

Thanks!