CSCI 275: Programming Abstractions

Lecture 13: Types

Fall 2024

Stephen Checkoway
Slides from Molly Q Feldman

Questions? Concerns?

Reminder: Structs

Reminder: Struct Data Types

`(struct name (field-a field-b) …)`

Racket has a very general mechanism for creating data structures and their associated procedures 🎉

To create our point data type, we can instead use

```
(struct point (x y))
```

This will create a new type named point *and the following procedures*:

`(point x y)` produces a new point with the given coordinates
`(point? obj)` returns `#t` if `obj` is a `point`
`(point-x p)` returns the `x` field
`(point-y p)` returns the `y` field

Example point

```
(struct point (x y))

(define p (point 3 4))

(point? p) ; returns #t

(point? 10) ; returns #f

(point-x p) ; returns 3

(point-y p) ; returns 4

p ; DrRacket prints this as #<point>

(point-x '(a b c)) ; raises an error
```

One more addition: Make the struct transparent

```
(struct point (x y) #:transparent)
```

`(point 3 4) => (point 3 4)` rather than #<point>

```
(equal? (point 3 4) (point 3 4)) => #t
```

`#:transparent` is a **keyword argument**

Why? Without it… Hard to Debug

```
(define (thing p)
  (cond [(negative? (point-x p))
         (error 'thing "Invalid point: ~s" p)]
        [else '...]))

(thing (point -3 2))
=> thing: Invalid point: #<point>
```

Why? Without it… Equality isn’t structural

```
; With lists, equal? performs structural
comparison
(equal? '(point 3 4) '(point 3 4)) => #t

; eq? asks if the arguments are the same object
(eq? '(point 3 4) '(point 3 4)) => #f

; With structs, equal? acts like eq? by
default!
(equal? (point 3 4) (point 3 4)) => #f
```

Let’s build a tree

complex recursive data type!

tree.rkt

Used heavily in
Part 2 of HW 4!

```
#lang racket
```

; Provide the procedures for working with trees.

```
(provide tree make-tree empty-tree
         tree? empty-tree? leaf?
         tree-value tree-children)
```

; Provide 8 example trees.

```
(provide empty-tree T1 T2 T3 T4 T5 T6 T7 T8)
```

Tree definition and a special value

; Definition of tree datatype

```
(struct tree (value children) #:transparent)
```

; An empty tree is represented by null

```
(define empty-tree null)
```

; `(empty-tree? empty-tree)` returns `#t`

```
(define empty-tree? null?)
```

; Convenience constructor

; (make-tree v c1 c2 ... cn) is equivalent to

; (tree v (list c1 c2 ... cn))

```
(define (make-tree value . children)
  (tree value children))
```

Reminder: variadic function!

Utility procedure

; Returns #t if the tree is a leaf.

```
(define (leaf? t)
  (cond [(empty-tree? t) #f]
        [(not (tree? t))
     (error 'leaf? "~s is not a tree" t)]
        [else (empty? (tree-children t))]))
```

Example (number) trees

```
(define T1 (make-tree 50))
(define T2 (make-tree 22))
(define T3 (make-tree 10))
(define T4 (make-tree 5))
(define T5 (make-tree 17))
(define T6 (make-tree 73 T1 T2 T3))
(define T7 (make-tree 100 T4 T5))
(define T8 (make-tree 16 T6 T7))
```

A tree is represented as a struct: `(tree value children)`.

If you want to count how many children a particular (nonempty) tree `t` has, what's the best way to do it?

A. `(length (tree-children t))`

B. `(length (third t))`

C. `(length (rest t))`

D. `(length (rest (rest t)))`

E. `(length (caddr t))`

Talking about Types

Why do languages have types?

Why do you think some languages have static types?

Why do you think some languages have dynamic types?

Dynamically-checked types

Dynamically-typed languages assign values types *at runtime*

In Racket, we can ask what the type of a value is:
`number?`, `list?`, `pair?`, `boolean?`, etc.

Functions are forced to check that the types of their input match the expected type

Racket and Python are examples of dynamically-typed languages

What does this code do?

```
(define (mul x y)
   (if (= x 0)
        0
        (* x y)))
(mul 0 'blah)
```

A. Syntax error
B. Contract violation
C. Runtime error
D. Warning about `'blah`
E. Returns 0

No explicit error checking!

```
(define (mul x y)
  (if (= x 0)
      0
      (* x y)))

(mul 10 'blah)
```

This gives a contract error:

```
*: contract violation
  expected: number?
  given: 'blah
```

Note that the contract error is on `*`, not `mul`

Implementing explicit error checking

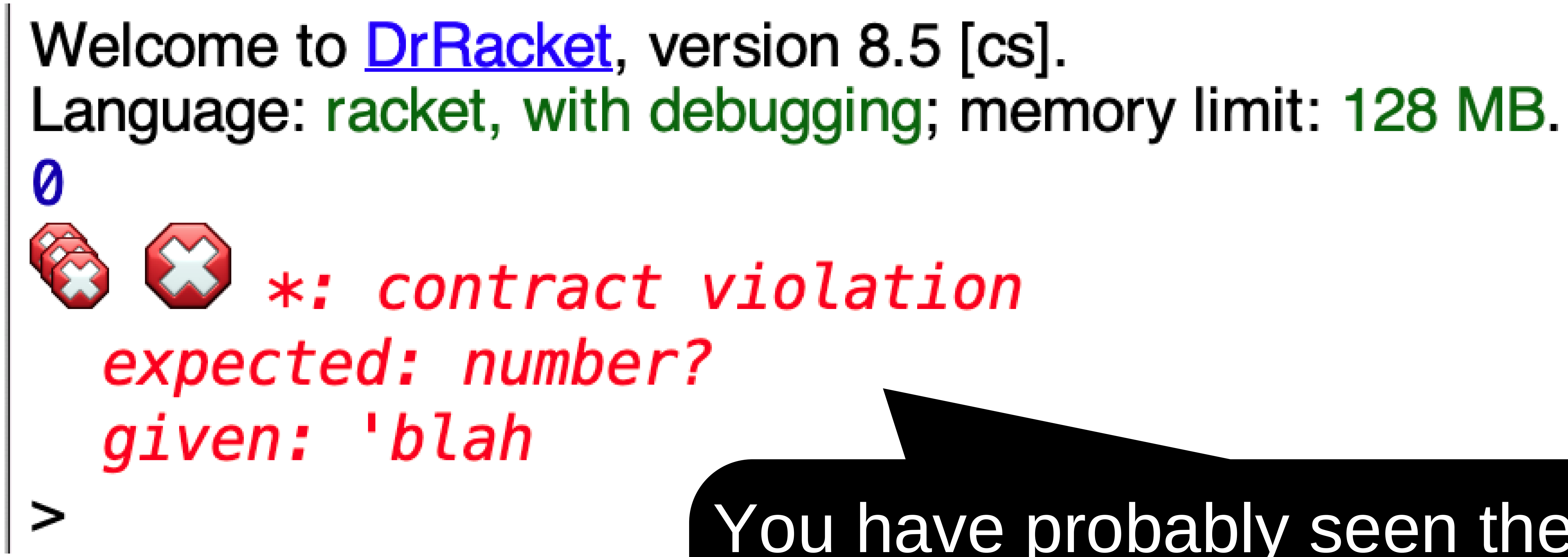
```
(define (mul x y)
  (cond [(not (number? x))
    (error 'mul "not a number: ~s" x)]
        [(not (number? y))
    (error 'mul "not a number: ~s" y)]
        [(= x 0) 0]
        [else (* x y)]))

(mul 0 'blah)
```

This gives the following error:

```
mul: not a number: blah
```

Aside: Contracts

Brief aside: Contracts



```
Welcome to DrRacket, version 8.5 [cs].
Language: racket, with debugging; memory limit: 128 MB.
0
*: contract violation
  expected: number?
  given: 'blah
>
```

You have probably seen these errors in all your Racket programming. But what exactly does “contract violation” mean here?

Brief aside: Contracts

Contracts are a predicate that declares some fact about a value that must be true

`number?` – The value is a number

`list?` – The value is a list

`positive?` – The value is positive

`pair?` – The value is a cons cell

`any/c` – Every value satisfies this contract

Contracts can help us do runtime error checking!

```
(define/contract (mul x y)
  ; x, y, and return value are numbers
  (-> number? number? number?)
  (if (= x 0)
      0
      (* x y)))
(mul 0 'blah)
```

This gives a contract error:

```
mul: contract violation
  expected: number?
  given: 'blah
  in: the 2nd argument of
      (-> number? number? number?)
```

Challenges of Dynamic Typing

Errors like passing and returning the wrong types of values are not caught until run time, even with contracts

```
(define/contract (faclist n)
  (-> positive? (listof integer?))
  (cond [(equal? n 1) 1]
        [ else (cons n (faclist (sub1 n)))]))
```

This has a type error, but it won't be caught until runtime

```
faclist: broke its own contract
  promised: list?
  produced: '(6 5 4 3 2 . 1)
```

Statically-checked types

Statically-typed languages compute a static approximation of the runtime types

The type of an expression is computed from the types of its sub expressions

This can be used to rule out a whole class of type errors at compile time

C, Java, Rust, and Haskell are examples of statically-typed languages

A Decision!

For the rest of today, we’re going to talk about **static types**

We *could* have done a small vignette of a type functional programming language (Haskell, Ocaml, etc.)

A Decision!

For the rest of today, we're going to talk about **static types**

Really helpful because can give you a **direct** comparison between dynamic and statically typed languages

Would recommend Racket over Typed Racket though in *most cases*

Instead: we will discuss types using ***Typed Racket***

Also used in a Summary Problems

The presentation here is adapted, with thanks, from the Typed Racket Guide: https://docs.racket-lang.org/ts-guide/index.html

Adding Types to Racket

To start off with, what are the types we have available?

`Boolean`

`String`

`Number` – but also a complex hierarchy here including `Integer`, `Float-Complex`, etc.

Adding Types to Functions

We provide type signatures as follows:

```
(: function-name (-> input-type output-type))
```

Below is a sum method in Racket. What should its type signature be?

```
(define (asum x y)
  (+ x y))
```

A. `(: asum (-> Number Number))`

B. `(: asum (-> Number Number Number))`

C. `(: asum (-> (Listof Number) Number))`

D. Something else

Below is a sum method in Racket. What should its type signature be?

```
(define (bsum lst)
  (cond [(empty? lst) 0]
        [else (+ (first lst) (bsum (rest lst)))]))
```

A. `(: bsum (-> Number Number))`

B. `(: bsum (-> Number Number Number))`

C. `(: bsum (-> (Listof Number) Number))`

D. Something else

What is `Listof`?

We decided `(: bsum (-> (Listof Number) Number)`
is the type for summing the elements of a list.

`Listof` is **not** actually a type, but rather a **type constructor**

Supporting type constructors (for instance, lists, arrays, references) is non-trivial

`(Listof Integer)` is meaningful,
`(Listof Listof)` is not

Similarly, `(String String)` does not work

How can we support procedures that output multiple types?

Motivation: Racket’s `member` procedure has the following behavior

`(member 4 (list 1 2 3))` gives `#f`

`(member 2 (list 1 2 3))` gives `‘(2 3)`

So… how to state the return type if we want to write

```
(: member (-> Number (Listof Number) ???))
```

Answer is Union Types!

`Union` here is inspired by mathematical set union

```
;number specific member implementation
(: nmem (-> Number (Listof Number)
         (U False (Listof Number))))
(define (nmem x lst)
  ...))
```

Next Up

Homework 3 is due **Friday** at 11:59pm

- First Commit due **tonight**

CSCI 275: Programming Abstractions

Lecture 14: Types & Computation

Spring 2024

Molly Q Feldman
Oberlin College

Questions? Concerns?

Functional Language of the Week: Haskell

- Haskell was first released in 1990, started in 1987

- Language developed “by committee”

  “The committee's primary goal was to design a language that satisfied these constraints:

  1. It should be suitable for teaching, research, and applications, including building large systems.
  2. It should be completely described via the publication of a formal syntax and semantics.
  3. It should be freely available. Anyone should be permitted to implement the language and distribute it to whomever they please.
  4. It should be based on ideas that enjoy a wide consensus.
  5. It should reduce unnecessary diversity in functional programming languages.”

https://www.haskell.org/onlinereport/preface-jfp.html

Functional Language of the Week: Haskell

- Seen as a test bed for a lot of advanced PL features
  - The GHC (Glasgow Haskell Compiler) specifically has made a lot of innovations in compilers
- Its logo is a lambda! Described as a ”an advanced, purely functional programming language”
- Haskell operates with a lazy semantics (sometimes referred to as *call-by-need* semantics) – this is different than what Racket and most languages use, stay tuned!

Functional Language of the Week: Haskell

Implementations from https://en.wikipedia.org/wiki/Haskell

```haskell
factorial :: (Integral a) => a -> a

-- Using recursion (with the "ifthenelse" expression)
factorial n = if n < 2
              then 1
              else n * factorial (n - 1)

-- Using recursion (with pattern matching)
factorial 0 = 1
factorial n = n * factorial (n - 1)

-- Using a list and the "product" function
factorial n = product [1..n]

-- Using fold (implements "product")
factorial n = foldl (*) 1 [1..n]
```

If you're interested, Simon Peyton Jones (main lead of the Haskell compiler) hour long talk on Haskell history:
https://www.youtube.com/watch?v=re96UgMk6GQ

Types Continued

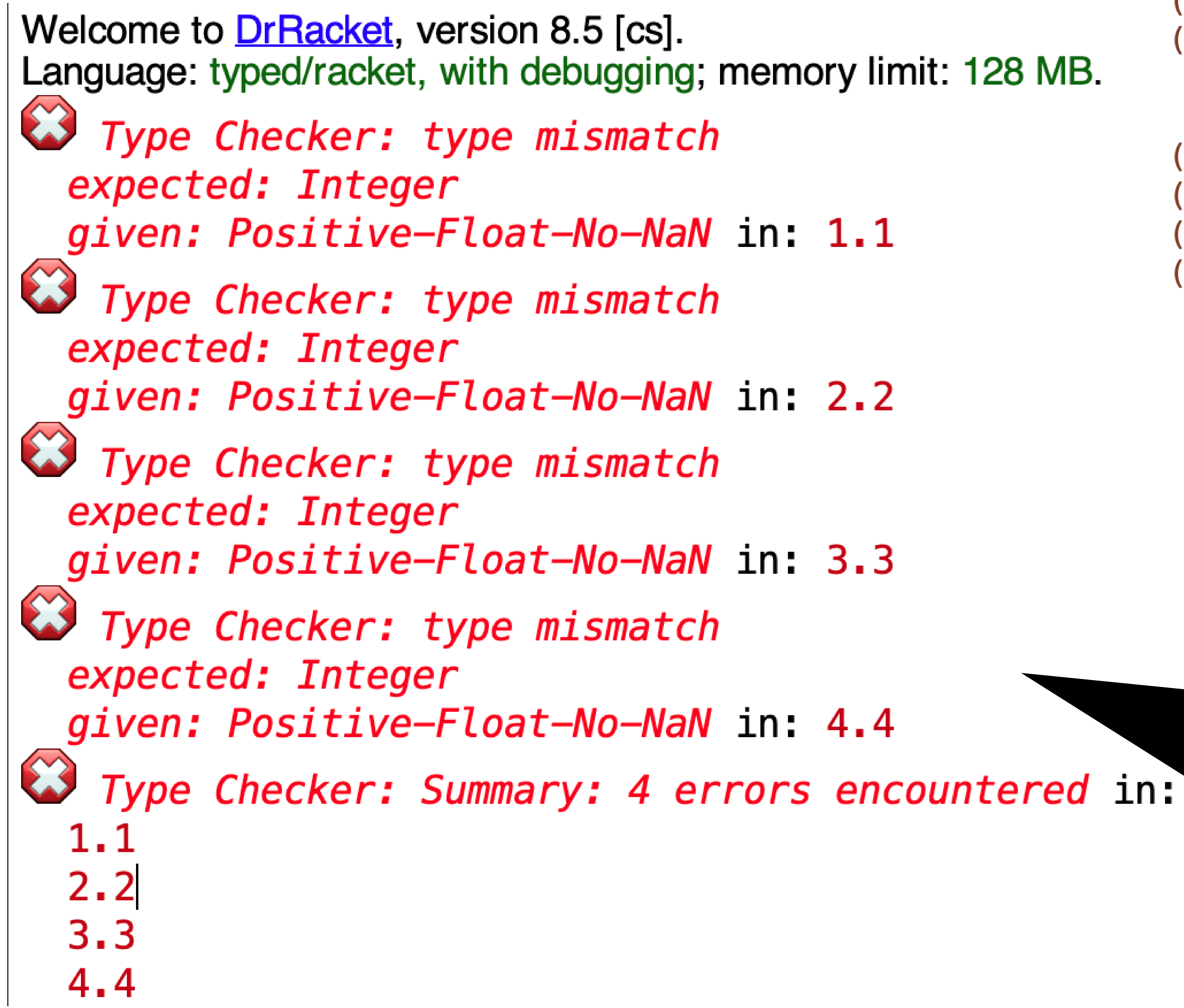
Which of the calls below will fail the type checker?

```
(: bsum (-> (Listof Number) Number))
(define (bsum lst)
  (cond [(empty? lst) 0]
        [else (+ (first lst) (bsum (rest lst)))]))

(: csum (-> (Listof Integer) Integer))
(define (csum lst)
  (foldr + 0 lst))

(bsum (list 1 2 3 4)) ;A
(bsum (list 1.1 2.2 3.3 4.4)) ;B
(csum (list 1 2 3 4)) ;C
(csum (list 1.1 2.2 3.3 4.4)) ;D
```

E. None of the above

Type Checking in Racket

```
(: bsum (-> (Listof Number) Number))
(define (bsum lst)
  (cond [(empty? lst) 0]
        [else (+ (first lst) (bsum (rest lst)))]))

(: csum (-> (Listof Integer) Integer))
(define (csum lst)
  (foldr + 0 lst))

(bsum (list 1 2 3 4)) ;A
(bsum (list 1.1 2.2 3.3 4.4)) ;B
(csum (list 1 2 3 4)) ;C
(csum (list 1.1 2.2 3.3 4.4)) ;D
```



```
Welcome to DrRacket, version 8.5 [cs].
Language: typed/racket, with debugging; memory limit: 128 MB.
Type Checker: type mismatch
 expected: Integer
 given: Positive-Float-No-NaN in: 1.1
Type Checker: type mismatch
 expected: Integer
 given: Positive-Float-No-NaN in: 2.2
Type Checker: type mismatch
 expected: Integer
 given: Positive-Float-No-NaN in: 3.3
Type Checker: type mismatch
 expected: Integer
 given: Positive-Float-No-NaN in: 4.4
Type Checker: Summary: 4 errors encountered in:
 1.1
 2.2
 3.3
 4.4
```

Notice even though D throws the error, we do not get any output from the previous three calls

Typed Racket includes a Type Checking Pass before evaluation!

Typed Racket

- Basic types like `Number`
- Function types like `(: negate (-> Integer Integer))`
- Type constructors like `(Listof Boolean)`
- Union types like `(U False (Listof Number))`

Creating your own types

Writing out type annotations is something we do a lot

AND

We probably want to be able to make new types for new data, etc

```
(define-type N3N (-> Number Number Number))

(define-type FalseNum (U False (Listof Number))
```

Reminder: Tree definition

; Definition of tree datatype
```
(struct tree (value children) #:transparent)
```

; An empty tree is represented by null
```
(define empty-tree null)
```

; `(empty-tree? empty-tree)` returns `#t`
```
(define empty-tree? null?)
```

; Convenience constructor
; (make-tree v c1 c2 ... cn) is equivalent to
; (tree v (list c1 c2 ... cn))
```
(define (make-tree value . children)
  (tree value children))
```

Reminder: variadic function!

How do we create a typed `Number` tree?

Reminder, the untyped version:

```
(struct tree (value children) #:transparent)
```

```
A. (struct tree ([value: Number]
       [children: (Listof tree)]))

B.(struct tree ([value: Number]
          [children: (Listof Number)]))

C.(struct tree ([value: Number] [children: Number]))

D.(struct tree ([value children] : Number))
```

E. Something else

Reminder of our leaf checker below. What type is it?

```
(define (leaf? t)
  (cond [(empty-tree? t) #f]
        [else (empty? (tree-children t))]))
```

```
A.  (: leaf? (-> tree tree))

B.(: leaf? (-> Boolean tree))

C.(: leaf (-> tree Boolean))

D.(: leaf (-> tree False))
```

E. Something else

Types for Variadic Functions

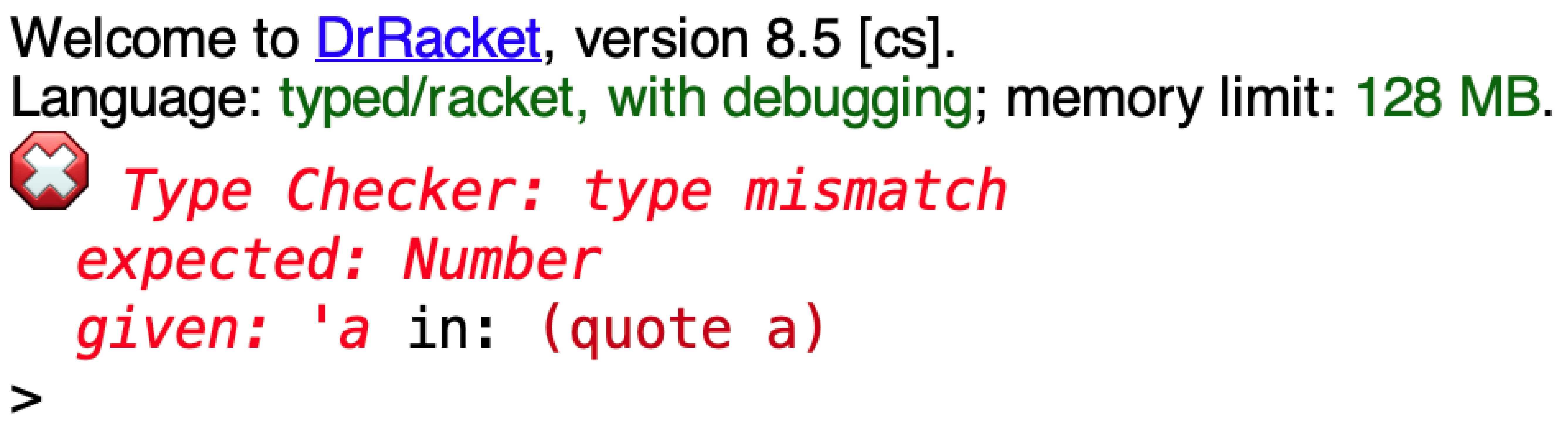
Specifies the type of the remaining arguments

```
(: make-tree (->* (Number) #:rest tree tree))
(define (make-tree value . children)
  (tree value children))
```

Reminder: variadic function!

Now we can *enforce* numeric trees!

```
(define T1 (make-tree 50))
(define T2 (make-tree 22))
(define T3 (make-tree 10))
(define T6 (make-tree 73 T1 T2 T3))

(define T4 (make-tree 'a)) ✖
```



```
Welcome to DrRacket, version 8.5 [cs].
Language: typed/racket, with debugging; memory limit: 128 MB.
 Type Checker: type mismatch
  expected: Number
  given: 'a in: (quote a)
>
```

Recursive Types

Struct typing is a special case of *Recursive Types*

We can define the `tree` type by saying that the children is of type "list of trees"

However, we cannot do something like

```
(define-type forest (U Number forest))
```

Type defined completely by its own definition

Types, Leveled Up

Assume we write 2 variants of the `member` procedure: one for Numbers, one for Strings. They have the type signatures:

```
(: nmem (-> Number (Listof Number)
            (U False (Listof Number))))
(: smem (-> String (Listof String)
            (U False (Listof String))))
```

Which of the following is true?

A. `nmem` and `smem` probably use the type of the arguments in their implementations
B. `nmem` and `smem` probably do *not* use the type of the arguments in their implementations
C. `nmem` and `smem`'s type signatures have the same general structure
D. More than one of the above
E. None of the above

We want a type signature for a general member!

```
(: nmem (-> Number (Listof Number)
            (U False (Listof Number))))
(: smem (-> String (Listof String)
            (U False (Listof String))))
```

```
(: mem (-> X (Listof X)
            (U False (Listof X))))
```

Parametric Polymorphism

Polymorph – ”Many forms”

Typed Racket (and many functional languages!) support **parametric polymorphism**

This allows us to write code *without knowing the actual type of the arguments*

parametric!

Parametric Polymorphism in Typed Racket

Typed Racket introduces the `All` type constructor

`All` takes a list of type variables and a body type – the type variable can be *free* in the body of the type

So for a general length method, we would get the type

```
(: length (All (A) (-> (Listof A) Integer)))
```

If this is the polymorphic type for `length`:

```
(: length (All (A) (-> (Listof A) Integer)))
```

what is it for our generic `mem` member procedure?

```
A. (: mem (-> A (Listof A)
              (U False (Listof A))))

B. (: mem (-> Number (Listof A)
              (U False (Listof A))))

C. (: mem (All (A) (-> A (Listof A)
              (U False (Listof A)))))
```

D. Something else

Other Types of Polymorphism

Always good to use an adjective when you're discussing polymorphism for this reason!

You likely have encountered other kinds of polymorphism!

Subtype Polymorphism: if you define a procedure for a Number, you can use it for a Float or an Integer as well ("subsumption rule")

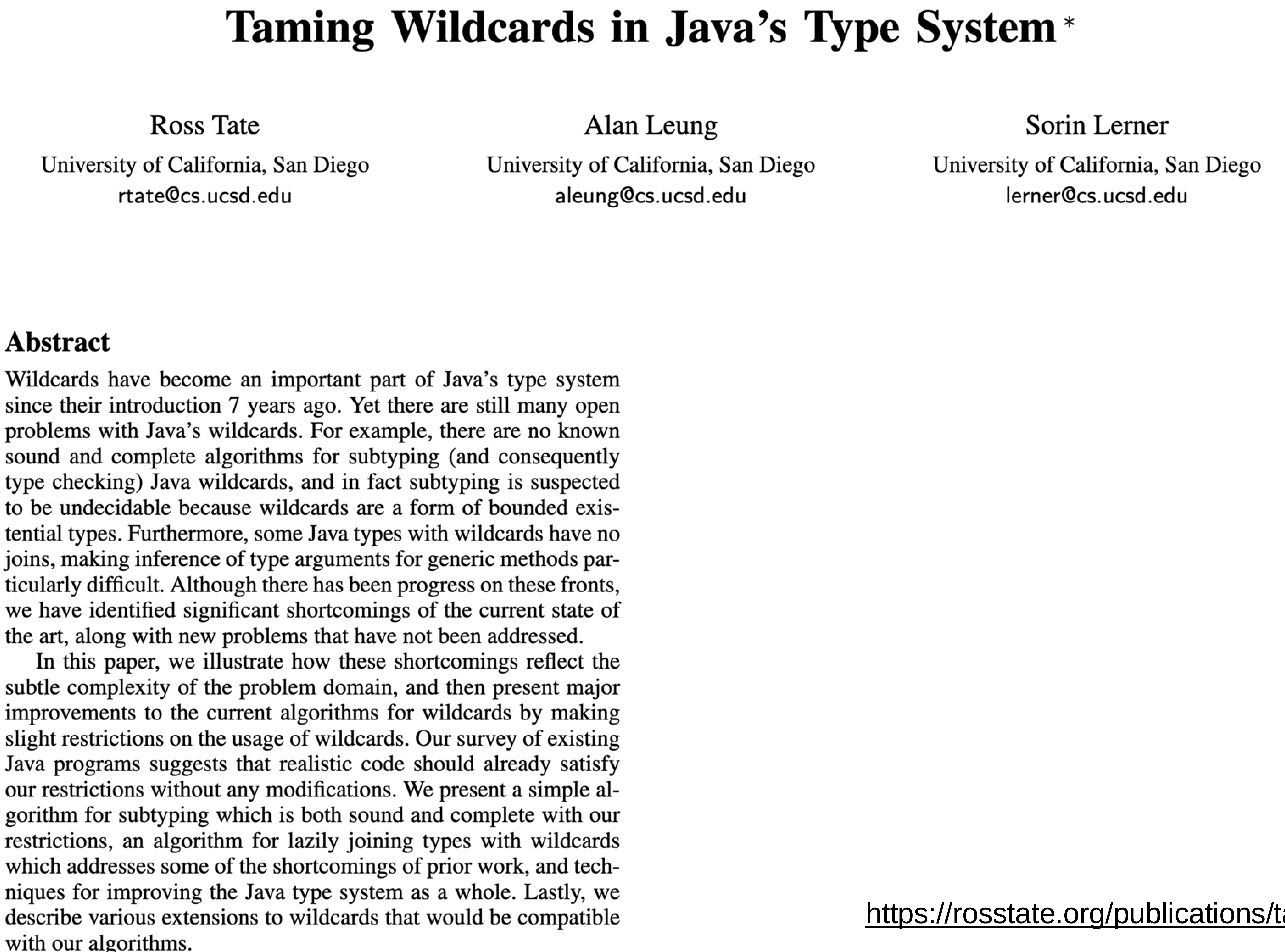
Ad-hoc Polymorphism: you can use the + operator on Strings and on Integers. You can also overload + for your own class! (this *looks* like polymorphism, but is many implementations)

Fun Facts

Java Generics are an implementation of parametric polymorphism using wildcards

This is a **new feature in Java, relatively speaking:** it was only added in 2004 and is based on decades of research by the PL community on generics in Java

Thanks to TAPL by Pierce and Steve Chong https://groups.seas.harvard.edu/courses/cs152/2015sp/lectures/lec14-polymorphism.pdf



Taming Wildcards in Java's Type System *

Ross Tate
University of California, San Diego
rtate@cs.ucsd.edu

Alan Leung
University of California, San Diego
aleung@cs.ucsd.edu

Sorin Lerner
University of California, San Diego
lerner@cs.ucsd.edu

Abstract

Wildcards have become an important part of Java's type system since their introduction 7 years ago. Yet there are still many open problems with Java's wildcards. For example, there are no known sound and complete algorithms for subtyping (and consequently type checking) Java wildcards, and in fact subtyping is suspected to be undecidable because wildcards are a form of bounded existential types. Furthermore, some Java types with wildcards have no joins, making inference of type arguments for generic methods particularly difficult. Although there has been progress on these fronts, we have identified significant shortcomings of the current state of the art, along with new problems that have not been addressed.

In this paper, we illustrate how these shortcomings reflect the subtle complexity of the problem domain, and then present major improvements to the current algorithms for wildcards by making slight restrictions on the usage of wildcards. Our survey of existing Java programs suggests that realistic code should already satisfy our restrictions without any modifications. We present a simple algorithm for subtyping which is both sound and complete with our restrictions, an algorithm for lazily joining types with wildcards which addresses some of the shortcomings of prior work, and techniques for improving the Java type system as a whole. Lastly, we describe various extensions to wildcards that would be compatible with our algorithms.

https://rosstate.org/publications/tamewild/tamewild-tate-pldi11.pdf

Fun Facts

Java Generics are an implementation of parametric polymorphism using wildcards

This is a **new feature in Java, relatively speaking:** it was only added in 2004 and is based on decades of research by the PL community on generics in Java

The classic model for parametric polymorphism is called System F (this was developed in the *1970s*)

Type-Related Algorithms

- Types give us additional functionality and the ability to do better error detection
- We would need some additional tools/time to go into these ideas in proper detail 😟

Type Checking

Are these types consistent?

Type Inference

Can I guess types in a consistent way?

Facts about Type-Related Algorithms

- Robin Milner won the Turing Award in 1991 partially for building “ML, the first language to include polymorphic type inference together with a type-safe exception-handling mechanism”
  - The most well-known type inference algorithm is called **Hindley-Milner type inference**

- Type inference in the full parametric polymorphism environment we talked about is undecidable

Type Inference Limits in Typed Racket

Typed Racket in it’s “Caveats and Limitations” notes “Typed Racket’s local type inference algorithm is currently not able to infer types for polymorphic functions that are used on higher-order arguments that are themselves polymorphic.”

Example that does type check:

```
(map cons '(a b c d) '(1 2 3 4))
```

`map` is polymorphic and `cons` is too - too much polymorphism!

Exam #1

Details of the Exam

Open book/notes/Racket – will specify specifically in the assignment

Programming problems & some conceptual questions related to programming

Two goals:

- Show you how much you know
- Show me your “intuitive” response to different topics

Logistics

Exam will go live at 10:49am next Tuesday and be due at the end of class (10:50am) on Wednesday (24 hours)

The exam will be released/submitted via Campuswire

During Wednesday's class, I will be in my office, feel free to stop by to ask any questions about the exam

Campuswire posts should **not be made, DM instead.** I will post any necessary clarifications on Campuswire as public posts, though, so please keep an eye out!

Possible question topics

Basic Scheme/Racket functions and special forms

- `cons`, `first` (`car`), `rest` (`cdr`), `list`, `member`, `empty?`, `filter`, etc.
- `define`, `lambda`, `if`, `cond`, `let`, `letrec`, `and`, `or`, etc.

`map` and `apply`

`foldl` and `foldr` and how they differ

Different design styles

- Tail recursion versus not tail recursion
- Higher-order functions
- letrec versus a helper function
- Currying

Closures

Next Up

Homework 3 is due **Friday** at 11:59pm

Homework 4 will go live later this week

No class on Friday!

No student hours tomorrow - questions via Campuswire

See you Monday!

Opportunities for help:

- Elise (Comp Skills) tonight/Sunday 7-9pm in King 225
- Isaac tomorrow 9:30 to 11am in King 225