

Typed Clojure in Theory and Practice

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Clojure



Dynamic typing

~\(\ツ)_



Functional style

(map f (filter g ...))



Lisp-style Macros

(for [...])



Immutable data structures



Hosted on JVM

Java



Immutable maps

Global function

```
(defn point [x y] {:x x, :y y})
```

Global definition

```
(def p (point 1 2))  
=> {:x 1 :y 2}
```

Assoc-iate entry

```
(assoc p :x 3)  
=> {:x 3 :y 2}
```

Dissoc-iate entry

```
(dissoc p :y)  
=> {:x 1}
```

Lookup entry

```
(get p :x)  
=> 1
```



Java interop

Java

```
(defn upper-case [s]
```

```
  (when s
```

```
    (.toUpperCase s)))
```

Method call

Null test

```
(upper-case nil)
```

```
;=> nil
```

```
(upper-case "abc")
```

```
;=> "ABC"
```



Macros

Macro definition

```
(defmacro when [t body]  
  `(if ~t ~body nil))
```

“Thread first” macro

```
(-> {} ; {}  
    (assoc :x 3) ; {:x 3}  
    (assoc :y 4)) ; {:x 3 :y 4}  
;=> {:x 3 :y 4}
```

“Thread last” macro

```
(->> [1 2 3 4] ; [1 2 3 4]  
      (map inc) ; (2 3 4 5)  
      (filter even?)) ; (2 4)  
;=> (2 4)
```



Higher-order functions

Update map entry

```
(-> {:ms 0}
      (update :ms inc))
;=> {:msg 1}
```

Create Mutable atom

```
(def tick (atom {:ms 0}))
```

Atomic swap

```
(swap! tick update :ms inc)
; {:ms 1}
```



Multimethods

Define multimethod

```
(defmulti subst
```

```
  “Apply substitution s on expression m.”
```

Dispatch on :op entry

```
  (fn [m s] (:op m))
```

“if” case

```
(defmethod subst :if [m s]
```

```
  (-> m
```

```
    (update :test subst s)
```

```
    (update :then subst s)
```

```
    (update :else subst s)))
```

“var” case

```
(defmethod subst :var [m s]
```

```
  (-> m
```

```
    (update :name #(or (get s %) %))))
```



Transducers

Transducers are composable, algorithmic transformations

Transducer definition `(def add-then-filter
 (comp (map inc)
 (filter even?)))`

Transducer usage `(sequence add-then-filter [1 2 3 4])
 => (2 4)`

Clojure's Runtime verification

Clojure.spec

Heterogeneous maps



Top-level Functions



Polymorphic functions



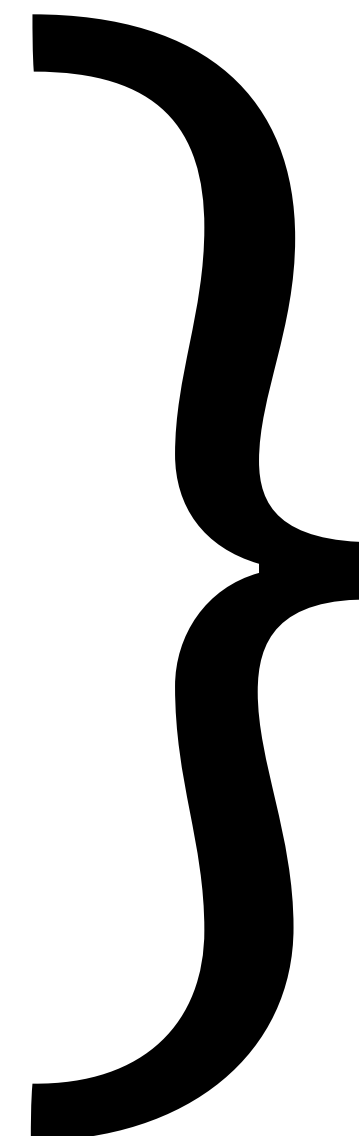
Transducers



Asynchronous Channels



Multimethods



***Better suited for
static analysis***

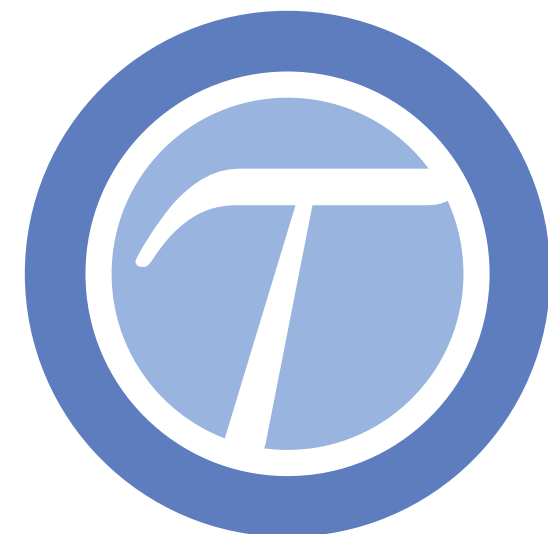


Clojure

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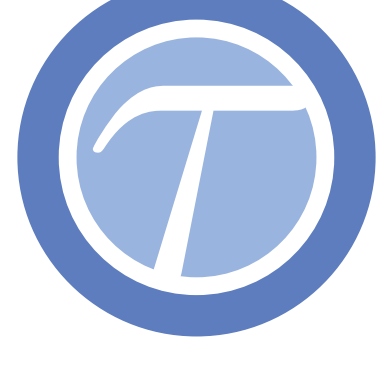
Optional Type
system

=



Typed Clojure

Typed Clojure

-  Bidirectional Type Checking
-  Check idiomatic Clojure code
-  Heterogeneous Maps
-  Occurrence typing (flow sensitive)
-  Prevents Null-pointer exceptions

Thesis Statement

Typed Clojure is a sound and practical optional type system for Clojure.

- Typed Clojure is an **optional type system for Clojure**.
- Typed Clojure is **sound**.
- Typed Clojure is **practical**.

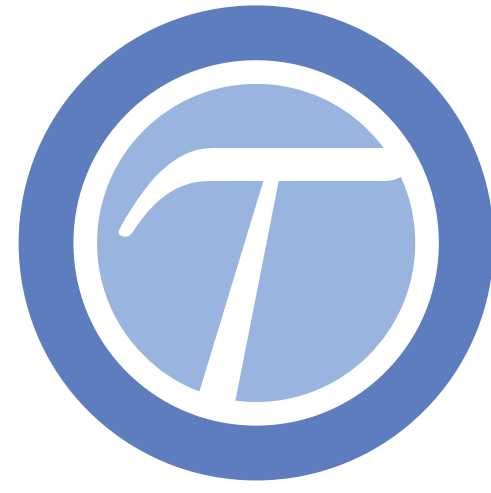
*Typed Clojure is a sound and practical
optional type system for Clojure.*

- Typed Clojure is an **optional type system for Clojure**.
 - Target idiomatic Clojure code
 - Type checking is opt-in
- Typed Clojure is **sound**.
 - Formal model of core type system features
 - Prove type soundness for model
- Typed Clojure is **practical**.
 - Type system supports actual Clojure usage patterns.
 - Address user feedback.

Thesis Statement

*Typed Clojure is a sound and practical
optional type system for Clojure.*

Part 1: Initial design & Evaluation



Bidirectional Type Checking

```
(ann upper-case [(U Str nil) -> (U Str nil)])  
(defn upper-case [s]  
  (when s  
    (.toUpperCase s)))
```

← *Top-level annotations*



Type-based control flow

*Explicit null
type*

```
(ann upper-case [(U Str nil) -> (U Str nil)])
```

```
(defn upper-case [s]
```

```
  (when s
```

Str

```
    (.toUpperCase s)))
```




*Refined
type via
occurrence typing*

Avoiding null-pointer exceptions

```
(ann upper-case [(U nil Str) -> (U nil Str)])  
(defn upper-case [s]  
  (when s ← (U nil Str)  
    (.toUpperCase s) ← Str)))
```

Evaluation
62/62 methods
avoid null-pointer
exceptions

Part 1: Initial design & Evaluation (completed)

- **Theory:** We formalize Typed Clojure, including its characteristic features like hash-maps, multimethods, and Java interoperability, and prove the model type sound.

- **Practice:** We present an empirical study of real-world Typed Clojure usage in over 19,000 lines of code, showing its features correspond to actual usage patterns.

- Published: “Practical Optional Types for Clojure”, Ambrose Bonnaire-Sergeant, Rowan Davies, Sam Tobin-Hochstadt; ESOP 2016


Thesis Statement

*Typed Clojure is a sound and practical
optional type system for Clojure.*

Part 1: Initial design & Evaluation

Part 2: Automatic Annotations


Annotations needed

```
(ann point [Long Long -> Point])  
(defn point [x y]  
  {:x x  
   :y y}))
```

Top-level
typed bindings



Untyped
libraries



```
(ann clojure.string/upper-case [Str -> Str])
```

Runtime Inference

```
(def forty-two 42)
```


$\Gamma = \{\text{forty-two} : \text{Long}\}$

```
(def forty-two  
  (track 42 ['forty-two]))
```

```
; Inference result:  
; ['forty-two] : Long  
(def forty-two 42)
```

Part 2: Automatic Annotations

(in progress)

- **Theory:** We design and formalize an approach to automatically generating top-level type annotations based on example executions. 
- **Practice:** We implement and evaluate our algorithm on real Clojure programs. We measure the reduction in the human annotation burden with an empirical study on the number of manual changes needed to type check a program.
- To be submitted: PLDI 2019 (Fall 2018)

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Part 1: Initial design & Evaluation

Part 2: Automatic Annotations

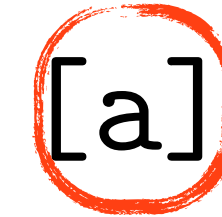
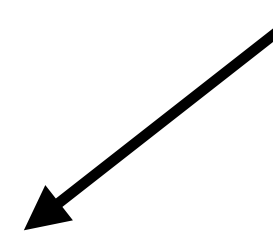
Part 3: Support checking more programs

Anonymous functions

Hard to check

```
(let [f (fn [a] (inc a))]  
      (f 1))
```

Need annotation!



Anonymous functions

Hard to check

```
(let [f (fn [a] (inc a))]  
      (f 1))
```

Need annotation!

Easier to check

```
(let [f ...]  
      ((fn [a] (inc a)) 1))
```

*Delay check to
occurrences*

Int



Polymorphic Higher-order functions

Hard to check (ann inc-val ['{:val Int} -> ' {:val Int}])
 (defn inc-val [m]
 (update m :val (fn [v] (inc v))))

*Polymorphic function cannot
propagate information to function
arguments (must check arguments
before solving polymorphic variables)*

Need type!

Polymorphic Higher-order functions

Hard to check `(ann inc-val ['{:val Int} -> ' {:val Int}])`
`(defn inc-val [m]`
 `(update m :val (fn [v] (inc v))))`

`(deftypeperule update [m k f]`
 ``(assoc ~m ~k (~f (get ~m ~k))))`

Polymorphic Higher-order functions

Hard to check `(ann inc-val ['{:val Int} -> ' {:val Int}])`
`(defn inc-val [m]`
 `(update m :val (fn [v] (inc v))))`

Easier to check

`(deftype-rule update [m k f]`
 ``(assoc ~m ~k (~f (get ~m ~k))))`

`(ann inc-val ['{:val Int} -> ' {:val Int}])`
`(defn inc-val [m]`
 `(assoc m :val ((fn [v] (inc v)) (get m :val))))`

Apply type rule

`Int`



Part 3: Support checking more programs (in progress) 🚧

- **Type checking interleaved with expansion:** We motivate and describe how to convert Typed Clojure from a type system that only checks fully expanded programs to one that incrementally checks partially expanded programs, and present an implementation. ✓
- **Extensible type rules:** We describe and implement an extensible system to define custom type rules for usages of top-level functions and macros and study how they improve the inference of core Clojure idioms.
- **Symbolic analysis:** We describe and implement symbolic evaluation strategies for Clojure programs and study how many more programs can be checked.

Thesis Statement

*Typed Clojure is a sound and practical
optional type system for Clojure.*


Part 1: Initial design & Evaluation

Part 2: Automatic Annotations

Part 3: Support checking more programs

(Backup Part 3: Automatic Annotations for clojure.spec)

Backup plan: Automatic Annotations for clojure.spec

Repurpose automation technology: We describe how to automatically generate clojure.spec annotations (“specs”) for existing programs by reusing most of the the infrastructure for automatic Typed Clojure annotations. We present a formal model of clojure.spec (an existing and popular runtime verification tool for Clojure) and implement the model in Redex. 

Test effectiveness of Annotation tool: Ensure high quality specs are generated, and automatically test over hundreds of projects.

Study how Clojure is used in real projects: We conduct a study of general Clojure idioms and practices by generating, enforcing, and exercising specs across hundreds of projects, as well as analyzing design choices in Typed Clojure’s type system, clojure.spec’s features, and our automatic annotation tool.

Timeline

<i>August 2018</i>	Finish formal model of Annotation Tool
<i>Sept-Oct 2018</i>	Carry out Auto Annotation experiments
<i>Nov 2018</i>	Submit PLDI paper for Auto Annotations
<i>Dec 2018</i>	Improve & evaluation Extensible typing rules
<i>Jan-May 2019</i>	Write dissertation
<i>June 2019</i>	Defend

Thanks