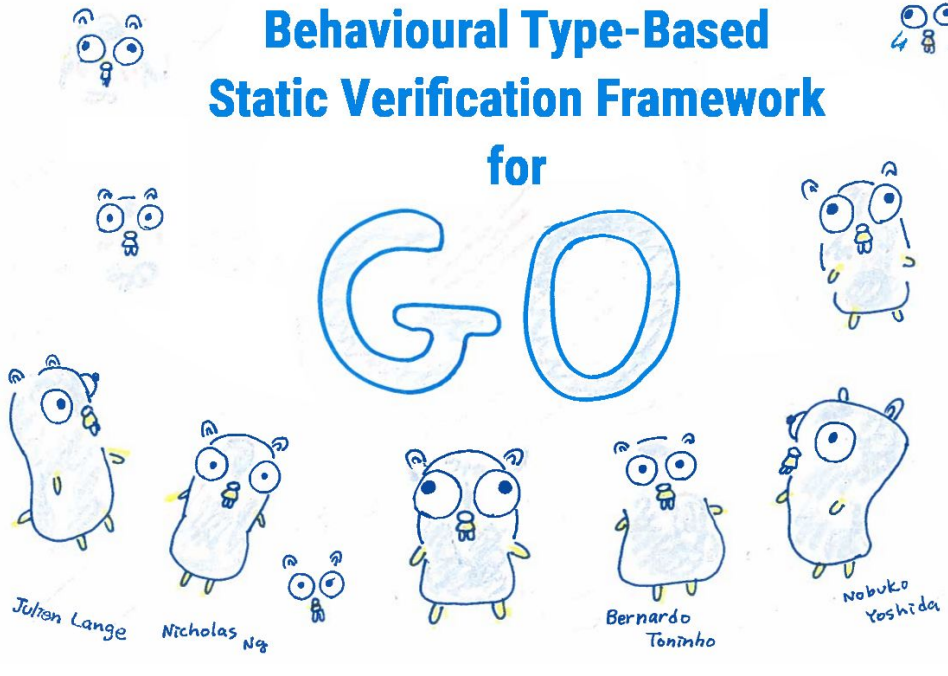
Behavioural Type-Based Static Verification Framework for Go



ETAPS 2019 TEST-OF-TIME AWARD

'Language primitives and type discipline for structured communication-based programming' by Kohei Honda, Vasco T. Vasconcelos and Makoto Kubo

POPL 2008 MOST INFLUENTIAL PAPER AWARD

LICS 2018 TEST OF TIME AWARD

LICS'98

A fully abstract game semantics for general references

Samson Abramsky Kohei Honda
LFCS, University of Edinburgh
{samson,kohei}@dcs.ed.ac.uk

Guy McCusker
St John's College, Oxford
mccusker@comlab.ox.ac.uk

Abstract

A games model of a programming language with higher-order store in the style of ML-references is introduced. The category used for the model is obtained by relaxing certain behavioural conditions on a category of games previously used to provide fully abstract models of pure functional languages. The model is shown to be fully abstract by means of factorization arguments which reduce the question of definability for the language with higher-order store to that for its purely functional fragment.

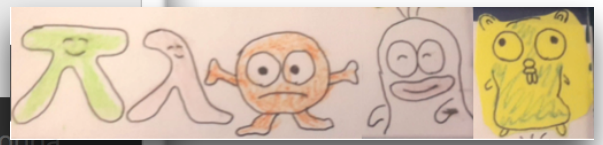
http://mrg.doc.ic.ac.uk

Mobility Research Group

session type

π-calculus, Session Types research at Imperial College

Home | People | Publications | Grants | Talks | Tutorials | Tools | Awards | Kohei Honda



NEWS

The paper *Multiparty asynchronous session types* by Kohei Honda, Nobuko Yoshida, and Marco Carbone, published in POPL 2008 has been awarded the ACM SIGPLAN Most Influential POPL Paper Award today at POPL 2018.

» more

10 Jan 2018

Estafet has published a page on their usage of the Scribble language developed in our group with RedHat and other industry partners.

» more

25 Sep 2017

Nick spoke at Golang UK 2017 on applying behavioural types to verify concurrent Go programs.

SELECTED PUBLICATIONS

2018

Julien Lange , Nicholas Ng , Bernardo Toninho , Nobuko Yoshida : A Static Verification Framework for Message Passing in Go using Behavioural Types. *To appear in* ICSE 2018 .

Bernardo Toninho , Nobuko Yoshida : Depending On Session Typed Process. *To appear in* FoSSaCS 2018 .

Bernardo Toninho , Nobuko Yoshida : On Polymorphic Sessions And Functions: A Talk of Two (Fully Abstract) Encodings. *To appear in* ESOP 2018 .

Rumyana Neykova , Raymond Hu , Nobuko Yoshida , Fahd Abdeljallal : Session Type Providers: Compile-time API Generation for Distributed Protocols with Interaction Refinements in F#. *To appear in* CC 2018 .

Post-docs:

Simon CASTELLAN

David CASTRO

Francisco FERREIRA

Raymond HU

Rumyana NEYKOVA

Nicholas NG

Alceste SCALAS

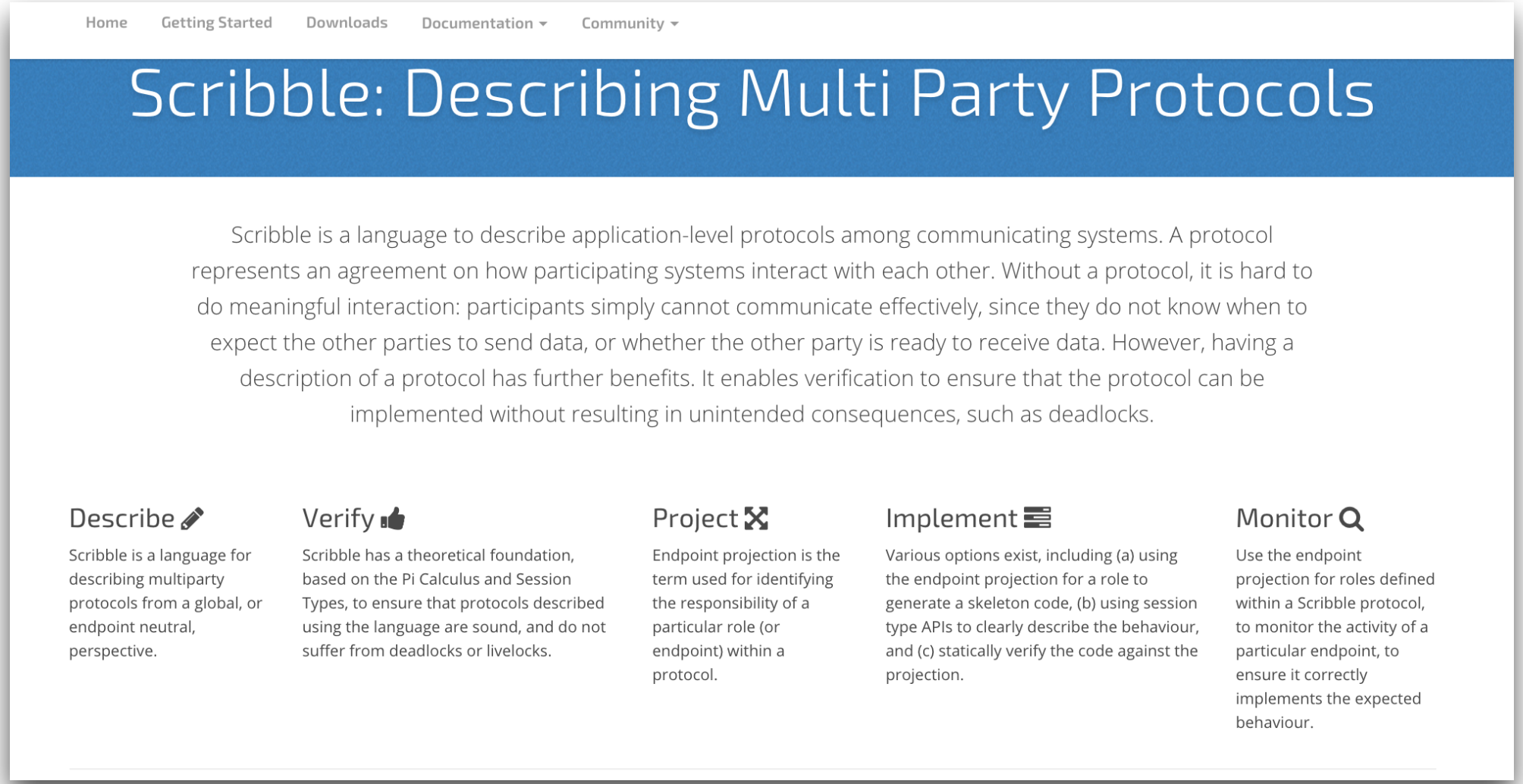
PhD Students:

Assel ALTAYEVA

Juliana FRANCO

Eva GRAVERSEN

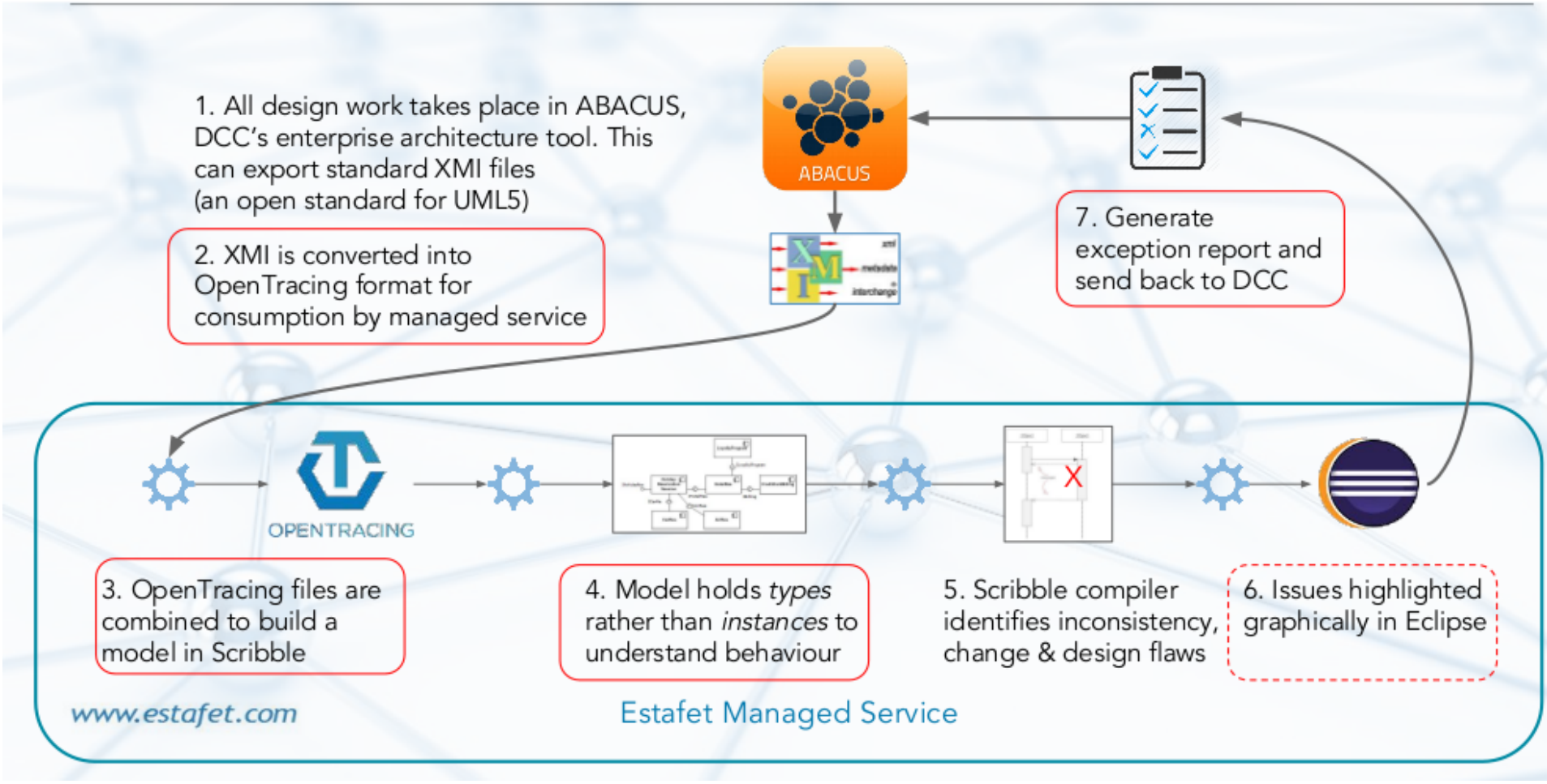
www.scribble.org



OOI Collaboration

- **TCS'16:** Monitoring Networks through Multiparty Session Types. Laura Bocchi , Tzu-Chun Chen , Romain Demangeon , Kohei Honda , Nobuko Yoshida
- **LMCS'16**: Multiparty Session Actors. Rumyana Neykova, Nobuko Yoshida
- **FMSD'15:** Practical interruptible conversations: Distributed dynamic verification with multiparty session types and Python. Romain Demangeon , Kohei Honda , Raymond Hu , Rumyana Neykova , Nobuko Yoshida
- **TGC'13:** The Scribble Protocol Language. Nobuko Yoshida , Raymond Hu , Rumyana Neykova , Nicholas Ng

End-to-End Switching Programme by DCC



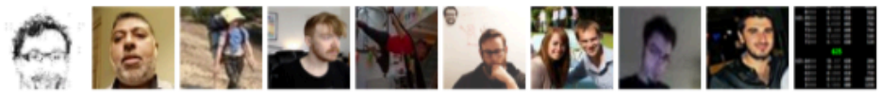
Interactions with Industries

CC'18

F#unctional Londoners Meetup G

6 days ago · 6:30 PM

Session Types with Fahd Abdeljallal



43 Members

Synopsis: Session types are a formalism to codify the structure of a communication, using types to specify the communication protocol used. This formalism provides the... LEARN MORE

ECOOP'17

…ributed Systems vs. Compositionality

Dr. Roland Kuhn
@rolandkuhn — *CTO of Actyx*

actyx

ECOOP'16

Current State

- behaviors can be composed both sequentially and concurrently
- effects are not yet tracked
- Scribble generator for Scala not yet there
- theoretical work at Imperial College, London (Prof. Nobuko Yoshida & Alceste Scalas)

CC'18

A Session Type Provider

Compile-Time API Generation of Distributed Protocols with Refinements in F#

Rumyana Neykova
Imperial College London
United Kingdom

Raymond Hu
Imperial College London
United Kingdom

Nobuko Yoshida
Imperial College London
United Kingdom

Fahd Abdeljallal
Imperial College London
United Kingdom

Abstract

We present a library for the specification and implementation of distributed protocols in native F# (and other .NET languages) based on multiparty session types (MPST). There are two main contributions. Our library is the first practical development of MPST to support what we refer to as *interaction refinements*: a collection of features related to the refinement of *protocols*, such as message-type refinements (value constraints) and message-value dependent control flow. A well-typed endpoint program using our library is guaranteed to perform only compliant session I/O actions conforming to the refined protocol, up to premature termination. Our library is developed as a session *type provider*,

1 Introduction

Type providers [20, 27] are a .NET feature for a form of compile-time meta programming, designed to bridge between programming in statically typed languages such as F# and C#, and working with so-called *information spaces*—structured data sources such as SQL databases or XML data.

A type provider works as a compiler plugin that performs on-demand generation of *types*: it takes a schema for an external information space, and generates types that allow the data to be manipulated via a strongly-typed interface, with benefits such as static error detection and IDE autocompletion. For example, an instantiation of the in-built type provider for WSDL Web services [6] may look like

POPL 2019 Research Papers

Write a Blog >>

15:21 - 16:27: Research Papers - Capabilities and Session Types I at POPL Track 2

15:21 - 15:43 ☆ *Talk*
StkTokens: Enforcing Well-Bracketed Control Flow and Stack Encapsulation Using Linear Capabilities
Lau Skorstengaard , Dominique Devriese Vrije Universiteit Brussel, Belgium, Lars Birkedal Aarhus University

15:43 - 16:05 ☆ *Talk*
Two sides of the same coin: Session Types and Game Semantics
Simon Castelan Imperial College London, UK, Nobuko Yoshida Imperial College London
DOI Pre-print

16:05 - 16:27 ☆ *Talk*
Exceptional Asynchronous Session Types: Session Types without Tiers
Simon Fowler The University of Edinburgh, Sam Lindley University of Edinburgh, UK, J. Garrett Morris University of Kansas, USA, Sara Décova
Pre-print

16:37 - 17:43: Research Papers - Session Types II at POPL Track 2

16:37 - 16:59 ☆ *Talk*
Interconnectability of Session-Based Logical Processes TOPLAS
Bernardo Toninho NOVA-LINCS, FCT/UNL, Nobuko Yoshida Imperial College London
DOI Pre-print

16:59 - 17:21 ☆ *Talk*
Distributed Programming using Role-Parametric Session Types in Go
David Castro Imperial College London, Raymond Hu Imperial College London, Sung-Shik Jongmans Open University of the Netherlands, Nicholas Ng Imperial College London, Nobuko Yoshida Imperial College London
DOI Pre-print

17:21 - 17:43 ☆ *Talk*
Less is More: Multiparty Session Types Revisited
Alceste Scalas Imperial College London, Nobuko Yoshida Imperial College London
DOI Pre-print

Selected Publications [2018-2019]

- [PLDI19] Alceste Scalas, NY, Elias Benussi: Verifying message-passing programs with dependent behavioural types.
- [CAV19] Julien Lange, NY: Verifying Asynchronous Interactions via Communicating Session Automata.
- [ECOOP19] Rupak Majumdar, Marcus Pirron, NY, and Damien Zufferey, Motion Session Types for Robotic Interactions
- [FoSSaCs19] Simon Castellan, NY: Causality in Linear Logic
- [ESOP19] Laura Bocchi, Maurizio Murgia, Vasco T. Vasconcelos, NY: Asynchronous Timed Session Types
- [POPL19] Simon Castellan, NY: Two Sides of the Same Coin: Session Types and Game Semantics
- [POPL19] David Castro, Raymond Hu, Sung-Shik Jongmans, Nicholas Ng, NY: Distributed Programming Using Role Parametric Session Types in Go
- [POPL19] Alceste Scalas, Nobuko Yoshida: Less Is More: Multiparty Session Types Revisited
- [POPL19] Bernardo Toninho, NY: Interconnectability of Session Based Logical Processes
- [ICSE18] Julien Lange, Nicholas Ng, Bernardo Toninho, NY: A Static Verification Framework for Message Passing in Go using Behavioural Types
- [LICS18] Romain Demangeon, NY: Causal Computational Complexity of Distributed Processes
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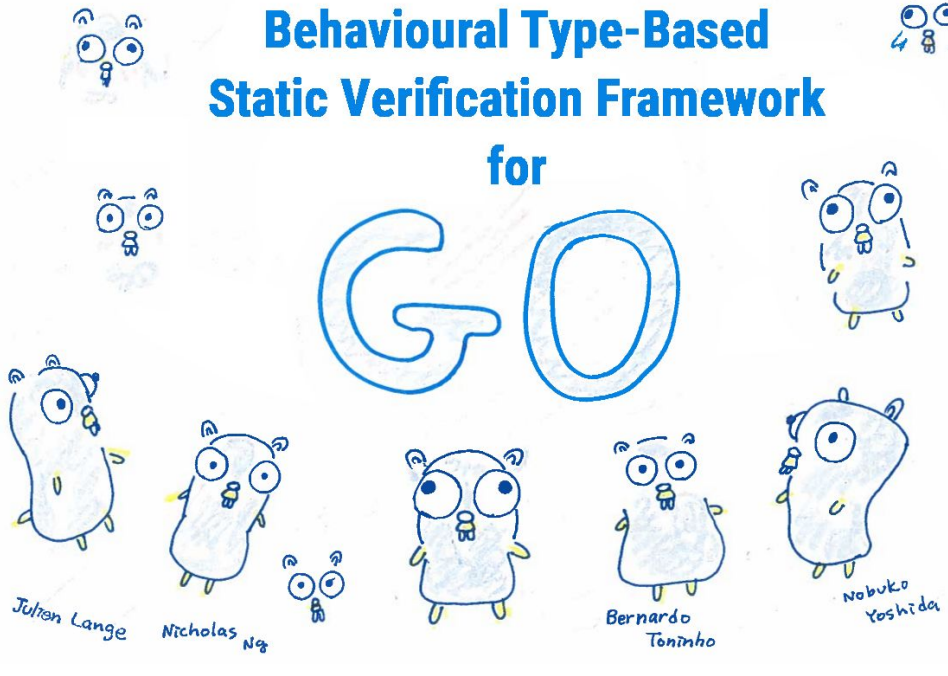

Imperial College London

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Go concurrency verification research at DoC grabs headline

POPL'17

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ICSE'18

the morning paper

an interesting/influential/important paper from the world of CS every weekday morning, as selected by Adrian Colyer

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A static verification framework for message passing in Go using behavioural types

JANUARY 25, 2018

tags: Concurrency, Programming Languages

A static verification framework for message passing in Go using behavioural types Lange et al., *ICSE 18*

With thanks to Alexis Richardson who first forwarded this paper to me.

We're jumping ahead to ICSE 18 now, and a paper that has been accepted for publication there later this year. It fits with the theme we've been exploring this week though, so I thought I'd cover it now. We've seen verification techniques applied in the context of **Rust** and **JavaScript**, looked at the integration of **linear types in Haskell**, and today it is the turn of Go!

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MOST READ IN THE LAST FEW DAYS

GO

programming language @ Google (2009)

- Message-Passing based multicore PL, successor of C
- *Do not communicate by shared memory; instead, share memory by communicating*

  Go Lang Proverb
- Explicit channel-based concurrency
  - Buffered I/O communication channels
  - Lightweight thread spawning — gorounines
  - Selective send / receive

CSP 80'

FUN

Dropbox, Netfix, Docker, CoreOS

- GO has a runtime deadlock detector
- How can we detect partial deadlock and channel errors for realistic programs?
- Use behavioural types in process calculi
  e.g. [ACM Survey, 2016] 185 citations, 6 pages

- Dynamic channel creations, unbounded thread creations, recursions,..
- Scalable (synchronous/asynchronous) Modular, Refinable

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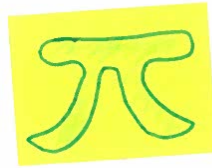

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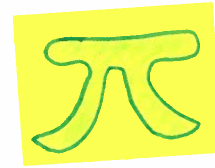

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186 ??

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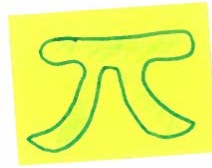

- Dynamic channel creations, unbounded thread creation[illegible]ons,..
- Scalable (synchronous/asynchronous) Modular, refinable

Understandable

Our Framework

STEP 1 Extract Behavioural Types

- (Most) Message passing features of GO
- Tricky primitives : selection, channel creation

STEP 2 Check Safety / Liveness of Behavioural Types

- Model-Checking (Finite Control)

STEP 3

- Relate Safety / Liveness of Behavioural Types and GO Programs
  - 3 Classes [POPL'17]
  - Termination Check

Our Framework

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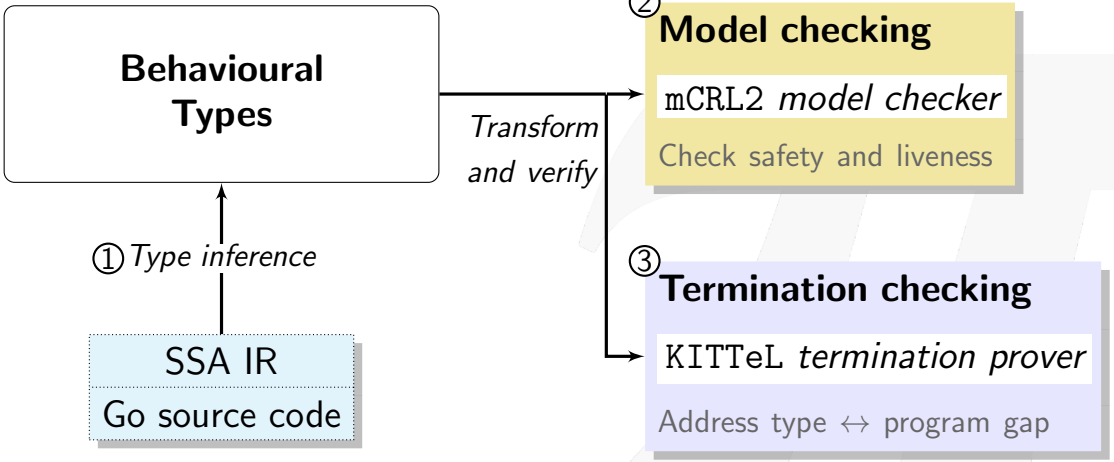
  - Termination Check

Static verification framework for Go

Overview



Concurrency in Go 

Goroutines

```
1  func main() {
2    ch := make(chan string)
3    go send(ch)
4    print(<-ch)
5    close(ch)
6  }
7
8  func send(ch chan string) {
9    ch <- "Hello Kent!"
10 }
```

`go` keyword + function call

- Spawns function as goroutine
- Runs in parallel to parent

Concurrency in Go 

Channels

```
1  func main() {
2    ch := make(chan string)
3    go send(ch)
4    print(<-ch)
5    close(ch)
6  }
7
8  func send(ch chan string) {
9    ch <- "Hello Kent!"
10 }
```

Create new channel
- Synchronous by default

Receive from channel

Close a channel
- No more values sent to it
- Can only close once

Send to channel

Concurrency in Go 

Channels

```
1  func main() {
2    ch := make(chan string)
3    go send(ch)
4    print(<-ch)
5    close(ch)
6  }
7
8  func send(ch chan string) {
9    ch <- "Hello Kent!"
10 }
```

Also `select-case`:

- Wait on multiple channel operations
- `switch-case` for communication

Concurrency in Go 

Deadlock detection

```
1  func main() {
2    ch := make(chan string)
3    go send(ch)
4    print(<-ch)
5    close(ch)
6  }
7
8  func send(ch chan string) {
9    ch <- "Hello Kent!"
10 }
```

- Send message thru channel
- Print message on screen

Output:

```
$ go run hello.go
Hello Kent!
$
```

Concurrency in Go 

Deadlock detection

Missing 'go' keyword

```
1  // import _ "net"
2  func main() {
3    ch := make(chan string)
4    send(ch) // Oops
5    print(<-ch)
6    close(ch)
7  }
8
9  func send(ch chan string) {
10   ch <- "Hello Kent!"
11 }
```

- Only one (main) goroutine
- Send without receive - blocks

Output:

```
$ go run deadlock.go
fatal error:  all goroutines
are asleep - deadlock!
$
```

Concurrency in Go 

Deadlock detection

Missing 'go' keyword

```
1  // import _ "net"
2  func main() {
3    ch := make(chan string)
4    send(ch) // Oops
5    print(<-ch)
6    close(ch)
7  }
8
9  func send(ch chan string) {
10   ch <- "Hello Kent!"
11 }
```

Go's **runtime** deadlock detector

- Checks if **all** goroutines are blocked ('global' deadlock)
- Print message then crash
- Some packages disable it (e.g. `net`)

Concurrency in Go 

Deadlock detection

Missing 'go' keyword

```
1  import _ "net" // unused
2  func main() {
3    ch := make(chan string)
4    send(ch) // Oops
5    print(<-ch)
6    close(ch)
7  }
8
9  func send(ch chan string) {
10   ch <- "Hello Kent"
11 }
```

Import unused, unrelated package

Concurrency in Go 

Deadlock detection

Missing 'go' keyword

```
1  import _ "net" // unused
2  func main() {
3    ch := make(chan string)
4    send(ch) // Oops
5    print(<-ch)
6    close(ch)
7  }
8
9  func send(ch chan string) {
10   ch <- "Hello Kent"
11 }
```

- Only one (main) goroutine
- Send without receive - blocks

Output:

```
$ go run deadlock2.go
```

Hangs: Deadlock **NOT** detected

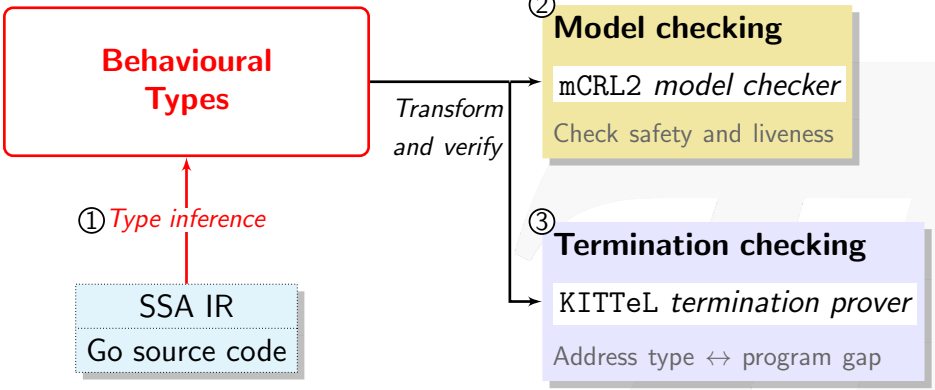
Our goal

Check liveness/safety properties **in addition to** global deadlocks

- Apply process calculi techniques to Go
- Use model checking to statically analyse Go programs

Behavioural type inference

Abstract Go communication as **Behavioural Types**



Infer Behavioural Types from Go program

Go source code

```
1  func main() {
2    ch := make(chan int)
3    go send(ch)
4    print(<-ch)
5    close(ch)
6  }
7
8  func send(c chan int) {
9    c <- 1
10 }
```

Behavioural Types

Types of CCS-like [Milner '80] process calculus

- Send/Receive
- new (channel)
- parallel composition (spawn)

Go-specific

- Close channel
- Select (guarded choice)

Infer Behavioural Types from Go program

Go source code

```
1  func main() {
2    ch := make(chan int)
3    go send(ch)
4    print(<-ch)
5    close(ch)
6  }
7
8  func send(c chan int) {
9    c <- 1
10 }
```

Inferred Behavioural Types

$$\rightarrow \left\{ \begin{array}{lcl} \mathsf{main}() & = & (\mathsf{new}\ ch); \\ & & (\mathsf{send}\langle \mathsf{ch} \rangle \mid \\ & & \mathsf{ch}; \\ & & \mathsf{close}\ \mathsf{ch}), \\ \\ \mathsf{send}(ch) & = & \overline{\mathsf{ch}} \end{array} \right\}$$

Infer Behavioural Types from Go program

Go source code

```
1  func main() {
2    ch := make(chan int)
3    go send(ch)
4    print(<-ch)
5    close(ch)
6  }
7
8  func send(c chan int) {
9    c <- 1
10 }
```

Inferred Behavioural Types

create channel → $\mathsf{main}() = (\mathtt{new}\ ch);$

spawn → $(\mathsf{send}\langle \mathsf{ch} \rangle \mid$

receive → $\mathsf{ch};$

close → $\mathtt{close}\ \mathsf{ch}),$

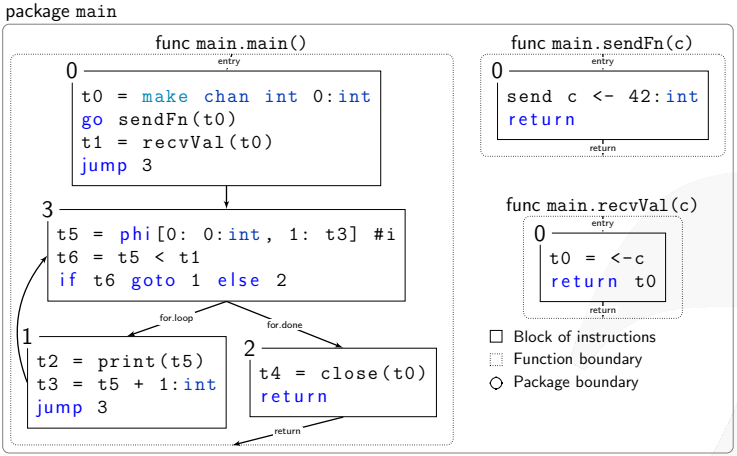
$\mathsf{send}(ch) = \overline{\mathsf{ch}}$

send

Infer Behavioural Types from Go program

```
1  func main() {
2      ch := make(chan int) // Create channel
3      go sendFn(ch)        // Run as goroutine
4      x := recvVal(ch)     // Function call
5      for i := 0; i < x; i++ {
6          print(i)
7      }
8      close(ch) // Close channel
9  }
10 func sendFn(c chan int)   { c <- 3 }   // Send to c
11 func recvVal(c chan int) int { return <-c } // Recv from c
```

Infer Behavioural Types from Go program



Analyse in

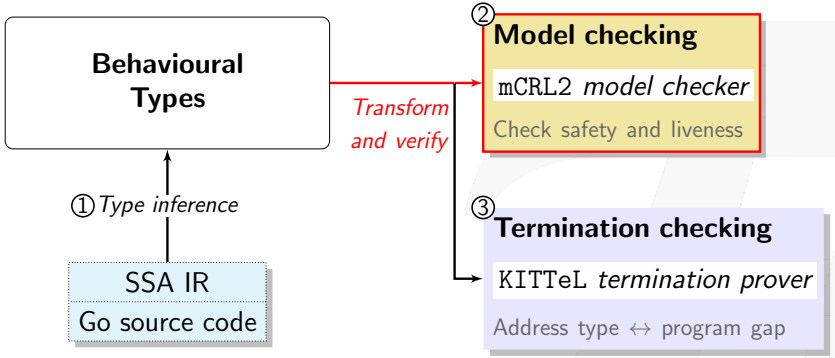
Static **S**ingle **A**ssignment

SSA representation of input program

- Only inspect **communication** primitives
- Distinguish between unique channels

Model checking behavioural types

From behavioural types to
model and **property specification**



Model checking behavioural types

$$\mathbf{M} \models \phi$$

- **LTS model** : inferred type + type semantics
- **Safety/liveness properties** : μ-calculus formulae for LTS
- Check with mCRL2 model checker
  - mCRL2 constraint: *Finite control* (no spawning in loops)

- Global deadlock freedom
- Channel safety (no send/`close` on closed channel)
- Liveness (partial deadlock freedom)
- Eventual reception

Behavioural Types as **LTS model**

Standard CS semantics, i.e.

$$\overline{a}; T \xrightarrow{\overline{a}} T$$

Send on channel a

$$\frac{T \xrightarrow{\overline{a}} T' \quad S \xrightarrow{a} S'}{T \mid S \xrightarrow{\tau_a} T' \mid S'}$$

Synchronise on a

$$a; T \xrightarrow{a} T$$

Receive on channel a

Behavioural Types as **LTS model**

Standard CS semantics, i.e.

$$\overline{a}; T \xrightarrow{\overline{a}} T$$

Send on channel a

$$\frac{T \xrightarrow{\overline{a}} T' \quad S \xrightarrow{a} S'}{T \mid S \xrightarrow{\tau_a} T' \mid S'}$$

Synchronise on a

$$a; T \xrightarrow{a} T$$

Receive on channel a

Specifying **properties** of model

Barbs (predicates at each state) describe property at state

- Concept from process calculi [Milner '88, Sangiorgi '92]
- μ-calculus properties specified in terms of barbs

Barbs ($T \downarrow_o$)

- Predicates of state/type T
- Holds when T is ready to fire action o

Specifying **properties** of model

$\overline{a}; T \downarrow_{\overline{a}}$

Ready to send

$$\frac{T \downarrow_{\overline{a}} \quad T' \downarrow_{a}}{T \mid T' \downarrow_{\tau_a}}$$

Ready to synchronise

$a; T \downarrow_{a}$

Ready to receive

Barbs ($T \downarrow_o$)

- Predicates of state/type T
- Holds when T is ready to fire action o

Specifying **properties** of model

$\overline{a}; T \downarrow_{\overline{a}}$

Ready to send

$$\frac{T \downarrow_{\overline{a}} \quad T' \downarrow_{a}}{T \mid T' \downarrow_{\tau_a}}$$

Ready to synchronise

$a; T \downarrow_{a}$

Ready to receive

Barbs ($T \downarrow_o$)

- Predicates of state/type T
- Holds when T is ready to fire action o

MiGo Liveness / Safety

$P \Downarrow a$

Barb [Milner & Sangiorgi 92]

Channel Safety

- Channel is closed at most once
- Can only input from a closed channel (default value)
- Others raise an error and crash

MiGo Liveness / Safety

$P \Downarrow a$

Barb [Milner & Sangiorgi 92]

Channel Safety

- Channel is closed at most once
- Can only input from a closed channel (default value)
- Others raise an error and crash

P is channel safe if $P \xrightarrow{*} (\nu \tilde{c}) Q$ and $Q \downarrow_{close(a)}$

$\neg(Q \downarrow_{end(a)}) \wedge \neg(Q \Downarrow \bar{a})$

a closed

never closing

never send

Migo Liveness / Safety

- **Liveness**

  All reachable actions are eventually performed

P is **live** if $P \rightarrow^{*}_{(\nu \tilde{c})} Q$

$$Q \downarrow a \Rightarrow Q \Downarrow \tau \text{ at } a$$

$$Q \downarrow \bar{a} \Rightarrow Q \Downarrow \tau \text{ at } a$$

Reduction (tau) at a

Select

Time Out

P_1 = select { a!, b?, z. P }

P_2 = select { a!, b? }

R_1 = a?

Select

P_1 = select { a!, b?, z. P }

Time Out

if P is live
P_1 is live

P_2 = select { a!, b? }

R_1 = a?

Select

P_1 = select { a!, b?, τ. P }

P_2 = select { a!, b? }

R_1 = a?

Time Out

if P is live
P_1 is live

P_2 is not live
$P_2 | R_2$ is

Select

$P_1 = \text{select}\ \{a!, b?, \tau.P\}$

$P_2 = \text{select}\ \{a!, b?\}$

$R_1 = a?$

Time Out

if P is live P_1 is live

P_2 is not live

$P_2 | R_2$ is

Barb $\downarrow \tilde{a}$

$$\frac{\pi_i \downarrow a_i}{\text{select}\ \{\pi_i.P_i\}_i \downarrow \tilde{a}} \qquad \frac{P \downarrow \tilde{a} \quad Q \downarrow \bar{a_i}}{P|Q \downarrow [a_i]}$$

Liveness $Q \downarrow \tilde{a} \Rightarrow Q \Downarrow \tau$ at a_i

Specifying **properties** of model

Given

- **LTS model** from inferred behavioural types
- **Barbs** of the LTS model

Express **safety/liveness properties**

- As μ-calculus formulae
- In terms of the **model** and the **barbs**

- Global deadlock freedom
- Channel safety (no send/`close` on closed channel)
- Liveness (partial deadlock freedom)
- Eventual reception

Property: Global deadlock freedom

$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_a \vee \downarrow_{\bar{a}}\right) \implies \langle \mathbb{A} \rangle \texttt{true}$$

If a channel a is ready to receive or send,
then there must be a **next state** (i.e. not stuck)

$\mathcal{A}$ = set of all initialised channels $\quad$ $\mathbb{A}$ = set of all labels
$\Rightarrow$ Ready receive/send = not end of program.

Property: Global deadlock freedom

$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_a \vee \downarrow_{\overline{a}}\right) \implies \langle \mathbb{A} \rangle \mathtt{true}$$

```
1  import _ "net" // unused
2  func main() {
3      ch := make(chan string)
4      send(ch) // Oops
5      print(<-ch)
6      close(ch)
7  }
8
9  func send(ch chan string) {
10     ch <- "Hello Kent"
11 }
```

- Send ($\downarrow_{\overline{\mathtt{ch}}}$: line 10)
- No synchronisation
- No more reduction

Property: Channel safety

$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_{a^*}\right) \implies \neg(\downarrow_{\overline{a}} \vee \downarrow_{\texttt{clo}\, a})$$

Once a channel a is closed (a^*),
it will not be sent to, nor closed again ($\texttt{clo}\, a$)

Property: Channel safety

$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_{a^*}\right) \implies \neg\left(\downarrow_{\overline{a}} \vee \downarrow_{\texttt{clo}\, a}\right)$$

```
1  func main() {
2      ch := make(chan int)
3      go func(ch chan int) {
4          ch <- 1 // is ch closed?
5      }(ch)
6      close(ch)
7      <-ch
8  }
```

- $\downarrow_{\texttt{clo}\, \texttt{ch}}$ when `close(ch)`
- $\downarrow_{\texttt{ch}^*}$ fires after closed
- Send ($\downarrow_{\overline{\texttt{ch}}}$: line 4)

Property: Liveness (partial deadlock freedom)

Liveness for Send/Receive

$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_a \vee \downarrow_{\overline{a}}\right) \implies \text{eventually}\left(\langle \tau_a \rangle \texttt{true}\right)$$

If a channel is ready to receive or send,
then **eventually**
it can synchronise (τ_a)

(i.e. there's corresponding send for receiver/recv for sender)

Property: Liveness (partial deadlock freedom)

Liveness for Send/Receive

$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_a \vee \downarrow_{\bar{a}}\right) \implies \text{eventually}\left(\langle \tau_a \rangle \texttt{true}\right)$$

where:

$$\text{eventually}\left(\phi\right) \stackrel{\text{def}}{=} \mu \mathbf{y}.\left(\phi \vee \langle \mathbb{A} \rangle \mathbf{y}\right)$$

If a channel is ready to receive or send,

then **for some reachable state**
it can synchronise (τ_a)

Property: Liveness (partial deadlock freedom)

Liveness for Select

$$\left(\bigwedge_{\tilde{a}\in\mathcal{P}(\mathcal{A})} \downarrow_{\tilde{a}}\right) \implies \text{eventually}\left(\langle\{\tau_a \mid a \in \tilde{a}\}\rangle \texttt{true}\right)$$

If one of the channels in `select` is ready to receive or send,
Then **eventually** it will synchronise (τ_a)

Property: Liveness (partial deadlock freedom)

Liveness for Select

$$\left(\bigwedge_{\tilde{a} \in \mathcal{P}(\mathcal{A})} \downarrow_{\tilde{a}}\right) \implies \text{eventually}\left(\langle \{\tau_a \mid a \in \tilde{a}\} \rangle \texttt{true}\right)$$

$$P_1 = \texttt{select}\{\overline{a},\ b,\ \tau.P\}$$
$$P_2 = \texttt{select}\{\overline{a},\ b\}$$
$$R_1 = a$$

P_1 is live if P is ✓

P_2 is not live ×

$(P_2 \mid R_1)$ is live ✓

Property: Liveness (partial deadlock freedom)

Liveness for Select

$$\Big(\bigwedge_{\tilde{a} \in \mathcal{P}(\mathcal{A})} \downarrow_{\tilde{a}}\Big) \implies \text{eventually}\,(\langle\{\tau_a \mid a \in \tilde{a}\}\rangle \texttt{true})$$

$$P_1 = \texttt{select}\{\overline{a},\ b,\ \tau.P\}$$
$$P_2 = \texttt{select}\{\overline{a},\ b\}$$
$$R_1 = a$$

P_1 is live if P is ✓

P_2 is not live ×

$(P_2 \mid R_1)$ is live ✓

Property: Liveness (partial deadlock freedom)

$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_a \vee \downarrow_{\overline{a}}\right) \implies \text{eventually}\,(\langle \tau_a \rangle \texttt{true})$$

$$\left(\bigwedge_{\tilde{a} \in \mathcal{P}(\mathcal{A})} \downarrow_{\tilde{a}}\right) \implies \text{eventually}\,(\langle \{\tau_a \mid a \in \tilde{a}\} \rangle \texttt{true})$$

```
1  func main() {
2      ch := make(chan int)
3      go looper() // !!!
4      <-ch        // No matching send
5  }
6  func looper() {
7      for {
8      }
9  }
```

× Runtime detector: Hangs

✓ Our tool: NOT live

Property: Liveness (partial deadlock freedom)

$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_a \vee \downarrow_{\bar{a}}\right) \implies \text{eventually}\left(\langle \tau_a \rangle \texttt{true}\right)$$

$$\left(\bigwedge_{\tilde{a} \in \mathcal{P}(\mathcal{A})} \downarrow_{\tilde{a}}\right) \implies \text{eventually}\left(\langle \{\tau_a \mid a \in \tilde{a}\} \rangle \texttt{true}\right)$$

```
1  func main() {
2      ch := make(chan int)
3      go loopSend(ch)
4      <-ch
5  }
6  func loopSend(ch chan int) {
7      for i := 0; i < 10; i-- {
8          // Does not terminate
9      }
10     ch <- 1
11 }
```

What about this one?

- Type: Live
- Program: NOT live

Needs additional guarantees

Property: Eventual reception

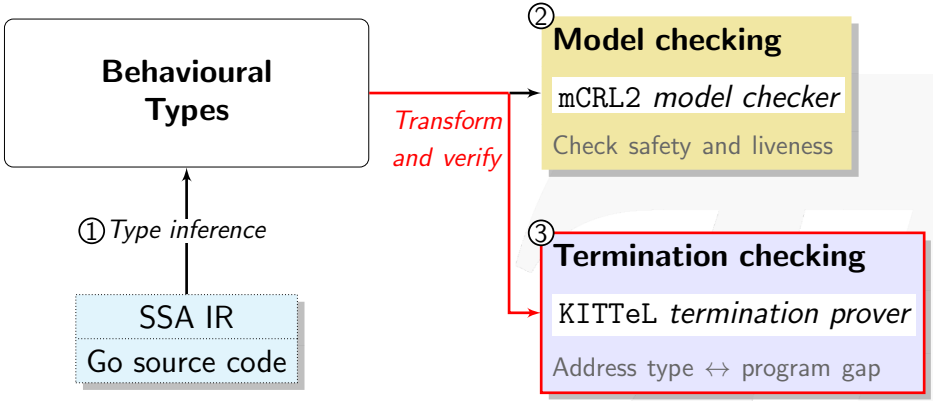
$$\left(\bigwedge_{a \in \mathcal{A}} \downarrow_{a^\bullet}\right) \implies \text{eventually}\,(\langle \tau_a \rangle \texttt{true})$$

If an item is sent to a buffered channel ($a^\bullet$),
Then **eventually** it can be consumed/synchronised (τ_a)

(i.e. no orphan messages)

Termination checking

Addressing the program-type *abstraction gap*



Termination checking with KITTeL

Type inference does not consider *program data*

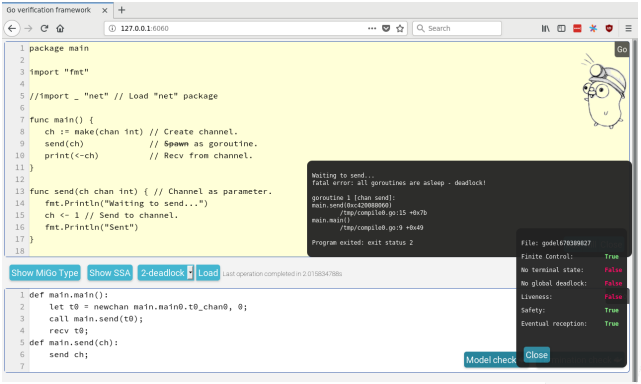
- Type liveness $\neq$ Program liveness if program non-terminating
- Especially when involving iteration

$\Rightarrow$ Check for loop termination

- If terminates, type liveness $=$ program liveness

	Program terminates	Program does not terminate
Type live	✓ Program live	?
Type not live	× Program not live	× Program not live

Tool: Godel-Checker



https://github.com/nickng/gospal

https://bitbucket.org/MobilityReadingGroup/godel-checker

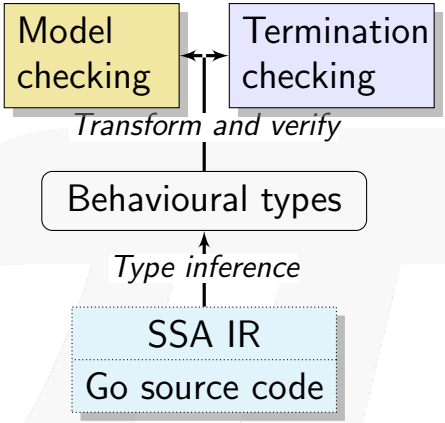
Understanding Concurrency with Behavioural Types

GolangUK Conference 2017

Conclusion

Verification framework based on
Behavioural Types

- Behavioural types for Go concurrency
- Infer types from Go source code
- Model check types for safety/liveness
- + termination for iterative Go code



In the paper

See our paper for omitted topics in this talk:

- Behavioural type inference algorithm
- Treatment of buffered (asynchronous) channels
- The `select` (non-deterministic choice) primitive
- Definitions of behavioural type semantics/barbs

Table 3: Go programs verified by our framework and comparison with existing static deadlock detection tools.

							Godel Checker				dingo-hunter [36]		gopherlyzer [40]		GoInfer/Gong [30]		
	Programs	LoC	# states	ψ_g	ψ_l	ψ_s	ψ_e	Infer	Live	Live+CS	Term	Live	Time	DF	Time	Live	CS	Time
1	mismatch [36]	29	53	×	×	✓	✓	620.7	996.8	996.7	✓	×	639.4	×	3956.4	×	✓	616.8
2	fixed [36]	27	16	✓	✓	✓	✓	624.4	996.5	996.3	✓	✓	603.1	✓	3166.3	✓	✓	601.0
3	fanin [36, 39]	41	39	✓	✓	✓	✓	631.1	996.2	996.2	✓	✓	608.9	✓	19.8	✓	✓	696.7
4	sieve [30, 36]	43	∞		*n/a*			-	-	-	*n/a*	*n/a*	-	*n/a*	-	✓	✓	778.3
5	philo [40]	41	65	×	×	✓	✓	6.1	996.5	996.6	✓	×	34.2	×	27.0	×	✓	16.8
6	dinephil3 [13, 33]	55	3838	✓	✓	✓	✓	645.2	996.4	996.3	✓	*n/a*	-	*n/a*	-	✓	✓	13.2 min
7	starvephil3	47	3151	×	×	✓	✓	628.2	996.5	996.5	✓	*n/a*	-	*n/a*	-	×	✓	3.5 min
8	sel [40]	22	103	×	×	✓	✓	4.2	996.7	996.6	✓	×	15.3	×	13.0	×	✓	50.5
9	selFixed [40]	22	20	✓	✓	✓	✓	4.0	996.3	996.4	✓	✓	14.9	✓	3168.3	✓	✓	13.1
10	jobsched [30]	43	43	✓	✓	✓	✓	632.7	996.7	1996.1	✓	*n/a*	-	✓	4753.6	✓	✓	635.2
11	forselect [30]	42	26	✓	✓	✓	✓	623.3	996.4	996.3	✓	✓	611.8	*n/a*	-	✓	✓	618.6
12	cond-recur [30]	37	12	✓	✓	✓	✓	4.0	996.2	996.2	✓	✓	9.4	*n/a*	-	✓	✓	14.7
13	concsys [42]	118	15	×	×	✓	✓	549.7	996.5	996.4	✓	*n/a*	-	×	5278.6	×	✓	521.3
14	alt-bit [30, 35]	70	112	✓	✓	✓	✓	634.4	996.3	996.3	✓	*n/a*	-	*n/a*	-	✓	✓	916.8
15	prod-cons	28	106	✓	×	✓	✓	4.1	996.4	1996.2	✓	×	10.1	×	30.1	×	✓	21.8
16	nonlive	16	8	✓	✓	✓	✓	630.1	996.6	996.5	timeout	⊗	613.6	*n/a*	-	⊗	✓	613.8
17	double-close	15	17	✓	✓	×	✓	3.5	996.6	1996.6	✓	☒	8.7	☒	11.8	✓	×	9.1
18	stuckmse	8	4	✓	✓	✓	×	3.5	996.6	996.6	✓	*n/a*	-	*n/a*	-	✓	✓	7.6

Future and related work

Extend framework to support more safety properties

Different verification approaches

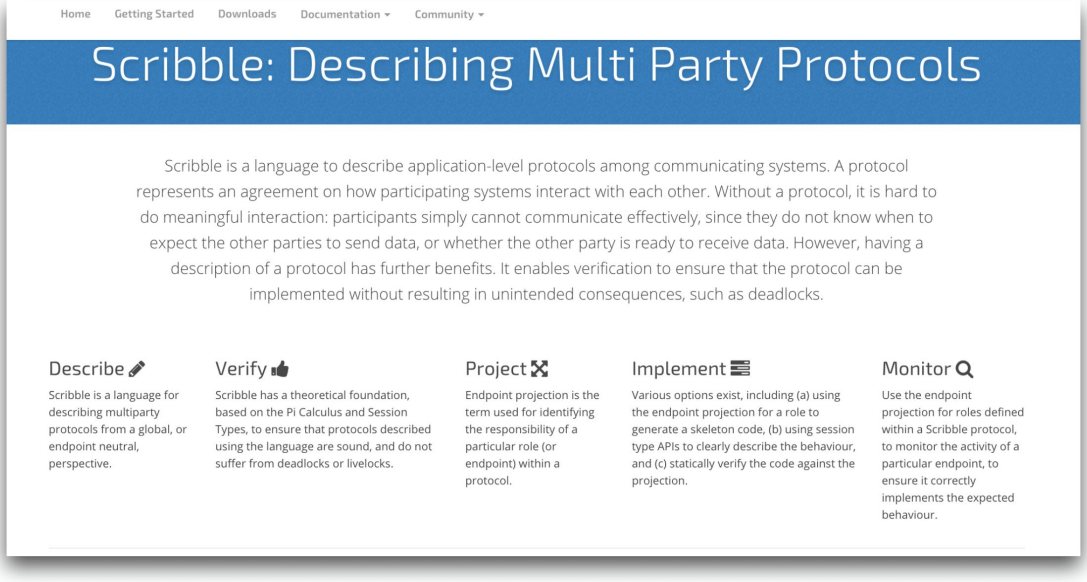
- Godel-Checker model checking [ICSE'18] (this talk)
- Gong type verifier [POPL'17]
- Choreography synthesis [CC'15]

Different concurrency issues (e.g. data races)

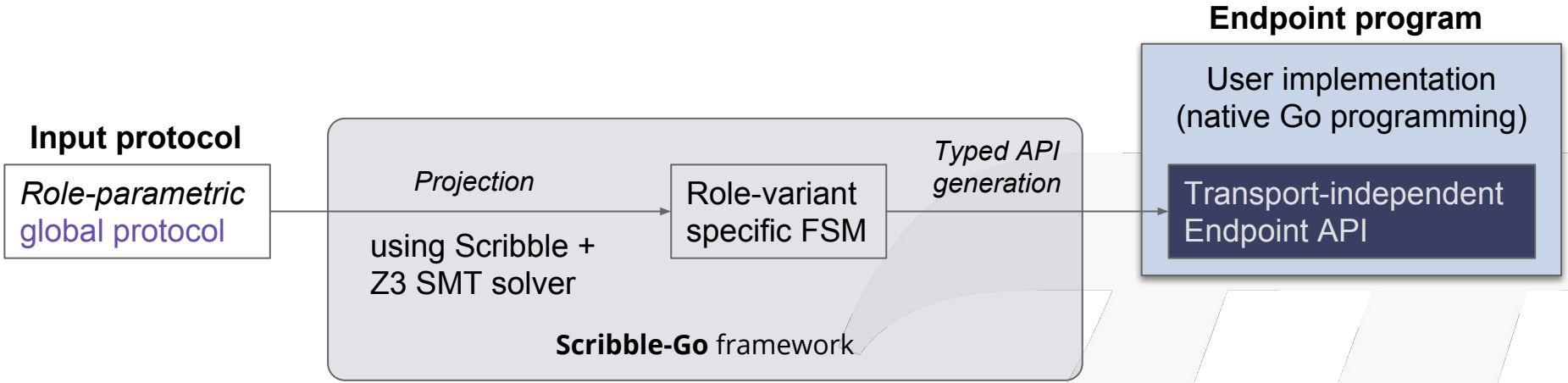
Distributed Programming using Role-Parametric Session Types in Go

David Castro, Raymond Hu, Sung-Shik Jongmans,
Nicholas Ng, Nobuko Yoshida

www.scribble.org



Scribble-Go workflow



1. Write a *role-parametric* global protocol
2. Select endpoint *role variant* to implement (e.g. `Fetcher`)
3. Use **Scribble-Go** to project and generate **Endpoint API**
4. Implement endpoint (e.g. `Fetcher[3]`) using the **Endpoint API**

Role variant

Role variant are *unique kinds* of endpoints

`{M, F[1..n], Server}`

If `F[1]` sends an extra request

HTTP HEAD to Server to get total size

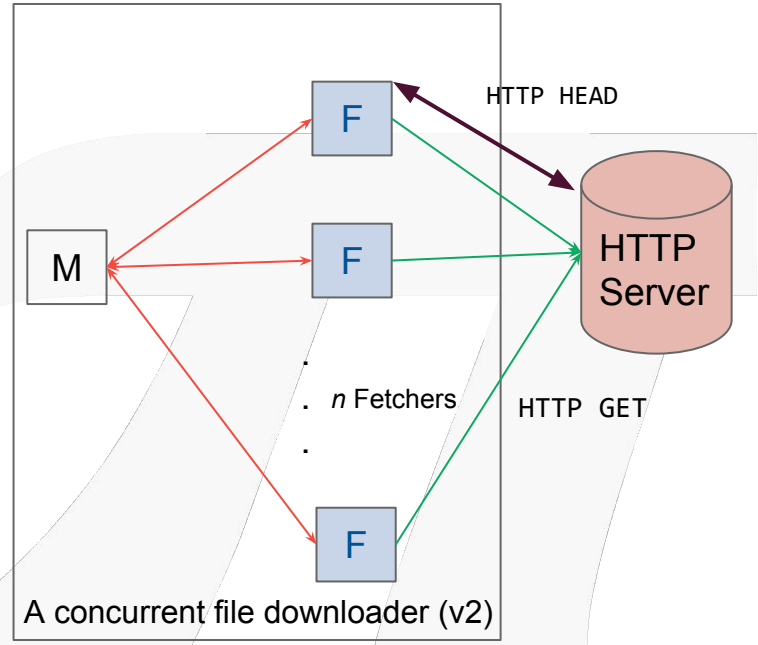
Then acts as a normal `F`

The role variants are:

`{M, F[1], F[2..n], Server}`

→ `F[1]` and `F[2..n]` are different endpoints

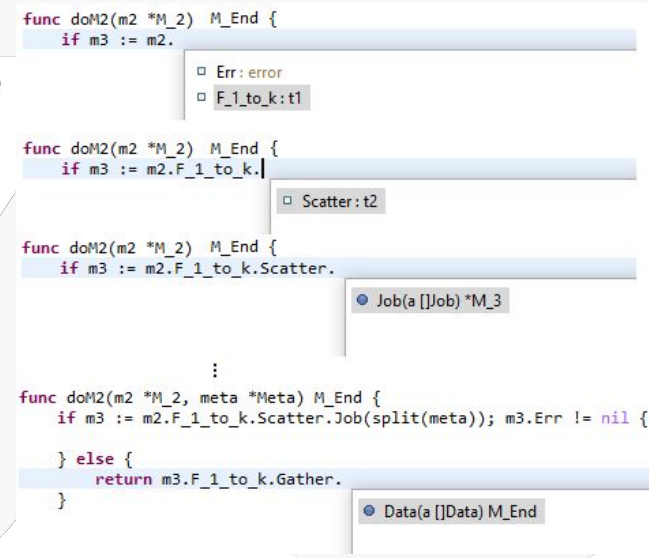
Inference of role variants (indices): formulated as SMT constraints for Z3



Endpoint API generation and usage

FSMs from local protocols → Message passing API

- Fluent-style
  - Every state is a unique type (struct)
  - Method calls (communication) returns next state
- Type information can be leveraged by IDEs
  - “dot-driven” content assist & auto complete



Behavioural Types for Go

Type syntax

$$
\begin{array}{rcl}
\alpha & \coloneqq & \overline{u} \mid u \mid \tau \\
T, S & \coloneqq & \alpha; T \mid T \oplus S \mid \&\{\alpha_i; T_i\}_{i \in I} \mid (T \mid S) \mid \mathbf{0} \\
 & \mid & (\texttt{new}\ a)T \mid \texttt{close}\ u; T \mid \mathbf{t}\langle \tilde{u} \rangle \mid \lfloor u \rfloor_k^n \mid buf[u]_{closed} \\
\mathbf{T} & \coloneqq & \{\mathbf{t}(\tilde{y}_i) = T_i\}_{i \in I}\ \texttt{in}\ S
\end{array}
$$

- Types of a CCS-like process calculus
- Abstracts Go concurrency primitives
  - Send/Recv, new (channel), parallel composition (spawn)
  - Go-specific: Close channel, Select (guarded choice)

Semantics of types

$$\text{SND}\ \overline{a};\ T \xrightarrow{\overline{a}} T \qquad \text{RCV}\ a;\ T \xrightarrow{a} T \qquad \text{TAU}\ \tau;\ T \xrightarrow{\tau} T$$

$$\text{END}\ \texttt{close}\,a;\ T \xrightarrow{\texttt{clo}\,a} T \qquad \text{BUF}\ \ \lfloor a \rfloor_k^n \xrightarrow{\overline{\texttt{clo}\,a}} buf[a]_{closed} \qquad \text{CLD}\ \ buf[a]_{closed} \xrightarrow{a^*} buf[a]_{closed}$$

$$\text{SEL}\ \frac{i \in \{1,2\}}{T_1 \oplus T_2 \xrightarrow{\tau} T_i} \qquad \text{BRA}\ \frac{\alpha_j;\ T_j \xrightarrow{\alpha_j} T_j \qquad j \in I}{\&\{\alpha_i;\ T_i\}_{i \in I} \xrightarrow{\alpha_j} T_j}$$

$$\text{PAR}\ \frac{T \xrightarrow{\alpha} T'}{T \mid S \xrightarrow{\alpha} T' \mid S} \qquad \text{SEQ}\ \frac{T \xrightarrow{\alpha} T'}{T;S \xrightarrow{\alpha} T';S} \qquad \text{TERM}\ \mathbf{0};S \xrightarrow{\tau} S$$

$$\text{COM}\ \frac{\alpha \in \{\overline{a}, a^*, a^\bullet\} \quad T \xrightarrow{\alpha} T' \quad S \xrightarrow{\beta} S' \quad \beta \in \{^\bullet a, a\}}{T \mid S \xrightarrow{\tau_a} T' \mid S'}$$

$$\text{EQ}\ \frac{T \equiv_\alpha T' \quad T' \xrightarrow{\alpha} T''}{T \xrightarrow{\alpha} T''} \qquad \text{DEF}\ \frac{T\{\tilde{a}/\tilde{x}\} \xrightarrow{\alpha} T' \quad \mathbf{t}(\tilde{x}) = T}{\mathbf{t}\langle \tilde{a} \rangle \xrightarrow{\alpha} T'}$$

$$\text{CLOSE}\ \frac{T \xrightarrow{\texttt{clo}\,a} T' \quad S \xrightarrow{\overline{\texttt{clo}\,a}} S'}{T \mid S \xrightarrow{\tau} T' \mid S'} \qquad \text{IN}\ \frac{k < n}{\lfloor a \rfloor_k^n \xrightarrow{^\bullet a} \lfloor a \rfloor_{k+1}^n} \qquad \text{OUT}\ \frac{k \geq 1}{\lfloor a \rfloor_k^n \xrightarrow{a^\bullet} \lfloor a \rfloor_{k-1}^n}$$

Barb predicates for types

$$a; T \downarrow_{a} \qquad \texttt{close}\, a; T \downarrow_{\texttt{clo}\, a} \qquad \frac{\forall i \in \{1, \ldots, n\} \,:\, \alpha_i \downarrow_{o_i}}{\&\{\alpha_i; T\}_{i \in \{1,\ldots,n\}} \downarrow_{\{o_1 \ldots o_n\}}}$$

$$\overline{a}; T \downarrow_{\overline{a}} \qquad \mathit{buf}[a]_{\mathit{closed}} \downarrow_{a^*}$$

$$\frac{T \downarrow_{o}}{T; T' \downarrow_{o}} \qquad \frac{T \downarrow_{a} \quad T' \downarrow_{\overline{a}} \text{ or } T' \downarrow_{a^*}}{T \mid T' \downarrow_{\tau_a}} \qquad \frac{T\,\{\tilde{a}/\tilde{x}\} \downarrow_{o} \quad \mathbf{t}(\tilde{x}) = T}{\mathbf{t}\langle \tilde{a} \rangle \downarrow_{o}}$$

$$\frac{T \downarrow_{a} \quad \alpha_i \downarrow_{\overline{a}}}{T \mid \&\{\alpha_i; S_i\}_{i \in I} \downarrow_{\tau_a}} \qquad \frac{T \downarrow_{\overline{a}} \text{ or } T \downarrow_{a^*} \quad \alpha_i \downarrow_{a}}{T \mid \&\{\alpha_i; S_i\}_{i \in I} \downarrow_{\tau_a}}$$

$$\frac{k < n}{\lfloor a \rfloor_k^n \downarrow_{\bullet a}} \qquad \frac{k \geq 1}{\lfloor a \rfloor_k^n \downarrow_{a\bullet}} \qquad \frac{T \downarrow_{\overline{a}} \quad T' \downarrow_{\bullet a}}{T \mid T' \downarrow_{\tau_a}} \qquad \frac{T \downarrow_{a\bullet} \quad \alpha_i \downarrow_{a}}{T \mid \&\{\alpha_i; S_i\}_{i \in I} \downarrow_{\tau_a}}$$

$$\frac{T \downarrow_{o}}{T \mid T' \downarrow_{o}} \qquad \frac{T \downarrow_{o} \quad a \notin \mathrm{fn}(o)}{(\mathrm{new}^n\, a); T \downarrow_{o}} \qquad \frac{T \downarrow_{o} \quad T \equiv T'}{T \downarrow_{o}}$$

Figure: Barb predicates for types.