

# Behavioural Type-Based Static Verification Framework

for

# GO



Julian Lange

Nicholas Ng

Bernardo  
Toninho

Nobuko  
Yoshida



## 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

# POPL 2008 MOST INFLUENTIAL PAPER AWARD



POPL 2008 Most Influential Paper Award

Kohei Honda, Nobuko Yoshida and Marco Carbone

Multiparty asynchronous session types





## Scribble: Describing Multi Party Protocols

Scribble is a language to describe application-level protocols among communicating systems. A protocol represents an agreement on how participating systems interact with each other. Without a protocol, it is hard to do meaningful interaction: participants simply cannot communicate effectively, since they do not know when to expect the other parties to send data, or whether the other party is ready to receive data. However, having a description of a protocol has further benefits. It enables verification to ensure that the protocol can be implemented without resulting in unintended consequences, such as deadlocks.

### Describe

Scribble is a language for describing multiparty protocols from a global, or endpoint neutral, perspective.

### Verify

Scribble has a theoretical foundation, based on the Pi Calculus and Session Types, to ensure that protocols described using the language are sound, and do not suffer from deadlocks or livelocks.

### Project

Endpoint projection is the term used for identifying the responsibility of a particular role (or endpoint) within a protocol.

### Implement

Various options exist, including (a) using the endpoint projection for a role to generate a skeleton code, (b) using session type APIs to clearly describe the behaviour, and (c) statically verify the code against the projection.

### Monitor

Use the endpoint projection for roles defined within a Scribble protocol, to monitor the activity of a particular endpoint, to ensure it correctly implements the expected behaviour.

# Online tool : <http://scribble.doc.ic.ac.uk/>

```
1 module examples;
2
3 global protocol HelloWorld(role Me, role World) {
4     hello() from Me to World;
5     choice at World {
6         goodMorning1() from World to Me;
7     } or {
8         goodMorning1() from World to Me;
9     }
10 }
11
```

Load a sample 

Check

Protocol:

Role:

Project

Generate Graph

# OOI Collaboration

**OOI OCEAN OBSERVATORY INITIATIVE**

**Location**  
CURRENT LOCATION

**Dashboard**  
RECENT IMAGES

**RECENT IMAGES**

- Glider  
Last Modified: 2012-02-01  
Last Viewed: 2012-02-01  
Last Updated: 2012-02-01 01:12:00
- Georgian Canal  
Last Modified: 2012-02-01  
Last Viewed: 2012-02-01  
Last Updated: 2012-02-01 01:12:00
- Acoustic Release  
Last Modified: 2012-02-01  
Last Viewed: 2012-02-01  
Last Updated: 2012-02-01 01:12:00

**POPULAR RESOURCES**

- Seafloor CDP  
Last Modified: 2012-02-01  
Last Viewed: 2012-02-01  
Last Updated: 2012-02-01 01:12:00
- Marine Litter  
Last Modified: 2012-02-01  
Last Viewed: 2012-02-01  
Last Updated: 2012-02-01 01:12:00
- Surface Buoy  
Last Modified: 2012-02-01  
Last Viewed: 2012-02-01  
Last Updated: 2012-02-01 01:12:00

**UPCOMING EVENTS**

- Oregon Coast Wave Height  
Last Modified: 2012-02-01  
Last Viewed: 2012-02-01  
Last Updated: 2012-02-01 01:12:00
- Water Surface Elevations  
Last Modified: 2012-02-01  
Last Viewed: 2012-02-01  
Last Updated: 2012-02-01 01:12:00

**RECENT UPDATES**

Thumbnail	Title	Date	Time	Category	Location	Status
	Oregon Coast Wave Height	2012-02-01 01:12:00	01:12:00	Wave	Oregon coast	Done
	California North Technology	2012-02-01 01:12:00	01:12:00	Technology	California	Done
	Oregon Coast Wave Height	2012-02-01 01:12:00	01:12:00	Wave	Oregon coast	Done
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**FOCUS LEGEND**

- Temperature
- Salinity
- Chlorophyll
- Sea Surface Height (SSH)
- Turbidity
- pH
- Dissolved Oxygen
- Other

**SEARCH**

**RESOURCES**

- All Resources
- Data Products
- Observations
- Platforms
- Instruments

**FOOTER**

National Science Foundation working with California for Ocean Leadership

Working for the Ocean through the National Science Foundation through a Cooperative Agreement with the participating Ocean Leadership. The OOI Program implements a Cooperative Agreement through web services from the System for Ocean Leadership.

**RELEASES** **RELATED** **COMPONENTS** **STATUS**

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

# End-to-End Switching Programme by DCC



**Estafet**

Innovate | Deliver | Transform

1. All design work takes place in ABACUS, DCC's enterprise architecture tool. This can export standard XML files (an open standard for UML5)

2. XML is converted into OpenTracing format for consumption by managed service



OPENTRACING



3. OpenTracing files are combined to build a model in Scribble

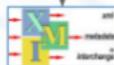
4. Model holds *types* rather than *instances* to understand behaviour

5. Scribble compiler identifies inconsistency, change & design flaws

6. Issues highlighted graphically in Eclipse

[www.estafet.com](http://www.estafet.com)

Estafet Managed Service



7. Generate exception report and send back to DCC

# End-to-End Switching Programme by DCC

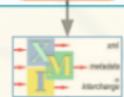


Estafet

Innovate | Deliver | Transform

## Caveats:

1. Using earlier implementation of Scribble (CDL), because we already have those tools
2. Using earlier plugin to Eclipse - we'd want to improve this
3. We're not going via OpenTracing - this is part of the bid costs



7. Generate exception report and send back to DCC

Scope of the demo



3. OpenTracing files are combined to build a model in Scribble



4. Model holds *types* rather than *instances* to understand behaviour



5. Scribble compiler identifies inconsistency, change & design flaws



6. Issues highlighted graphically in Eclipse

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Estafet Managed Service

# Interactions with Industries



Nobuko Yoshida  
Imperial College, London



Adam Bowen @adamnbowen · Sep 15

I didn't even know that session types existed an hour ago, but thanks to Nobuko Yoshida's great talk at [#pwlconf](#), I want to learn more.

## DoC researcher to speak at Golang UK conference

by Vicky Kapogianni  
20 July 2016



DoC researcher to speak at industry-focused Golang UK conference on results of concurrency research

[Click here to add content](#)



.@nicholaswng rocking on @GolangUKconf about static deadlock detection in #golang #gouk16



# Interactions with Industries

## #functional Londoners Meetup

CC'18

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

## Distributed Systems vs. Compositionality

Dr. Roland Kuhn  
@rolandkuhn — CTO of Actyx

actyx

### 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)

ECOOP'16

# Selected Publications 2017/2018

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- ▶ **[CC'18]** Romyana Neykova , Raymond Hu, NY, Fahd Abdeljallal: Session Type Providers: Compile-time API Generation for Distributed Protocols with Interaction Refinements in F#.
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- ▶ **[ICSE'18]** Julien Lange, Nicholas Ng, Bernardo Toninho, NY : A Static Verification Framework for Message Passing in Go using Behavioural Types
- ▶ **[ECOOP'17]** Alceste Scala, Raymond Hu, Ornela Darda, NY: A Linear Decomposition of Multiparty Sessions for Safe Distributed Programming..
- ▶ **[COORDINATION'17]** Keigo Imai, NY, Shoji Yuen: Session-ocaml: a session-based library with polarities and lenses.
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- ▶ **[CC'17]** Romyana Neykova, NY: Let It Recover: Multiparty Protocol-Induced Recovery.
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## Go concurrency verification research at DoC grabs headline

POPL'17

**A paper by DoC researchers at POPL on Go concurrency verification was featured in a tech blog and generates a buzz outside of the research community.**

A [paper](#) by researchers at the department was recently featured in the morning paper, a [blog](#) by venture capitalist Adrian Colye, which summarises an important, influential, topical or otherwise interesting paper in the field of computer science every weekday in an easily digestible way by non-researchers. On the [2 Feb 2017 issue](#) of the morning paper, It was highlighted as "the true spirit of POPL (Principles of Programming Languages)".

# the morning paper

ICSE'18

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!

### SUBSCRIBE



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### SEARCH

### ARCHIVES

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 - **goroutines**
  - Selective **send/receive**

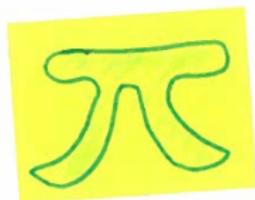
CSP<sub>80'</sub>

# FUN

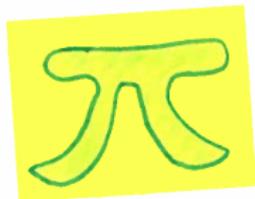
Dropbox, Netflix, Docker, CoreOS

- ▶ **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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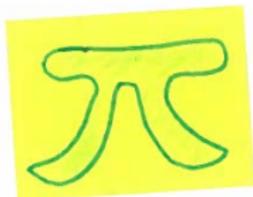


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186 ??

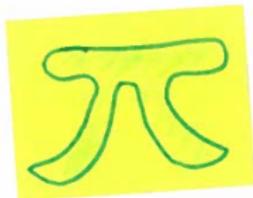
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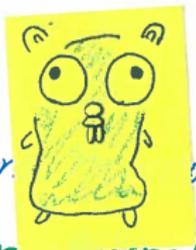
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▶ Dynamic channel creations, unbounded thread creations, ...

▶ **Scalable** (synchronous/asynchronous) **Modular**, **verifiable**



**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

## STEP 1 Extract Behavioural Types

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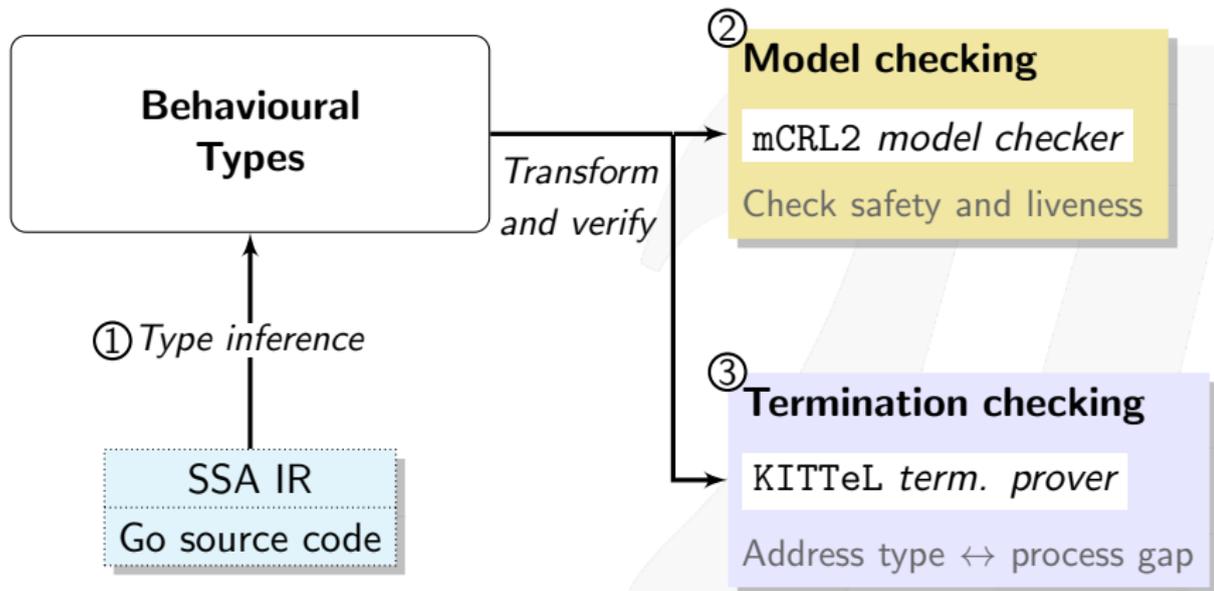
## STEP 3

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



# Static verification framework for Go

## Overview



# Concurrency in Go 🐼

## Concurrency primitives

```
1 func main() {
2     ch := make(chan int) // Create channel.
3     go send(ch)          // Spawn as goroutine.
4     print(<-ch)         // Recv from channel.
5 }
6
7 func send(ch chan int) { // Channel as parameter.
8     ch <- 1 // Send to channel.
9 }
```

- Send/receive blocks goroutines if channel full/empty resp.
- Channel buffer size specified at creation: `make(chan int, 1)`
- Other primitives:
  - Close a channel `close(ch)`
  - Guarded choice `select { case <-ch:; case <-ch2: }`

# Concurrency in Go

## Deadlock detection

```
1 func main() {  
2     ch := make(chan int) // Create channel.  
3     send(ch)             // Spawn as goroutine.  
4     print(<-ch)         // Recv from channel.  
5 }  
6  
7 func send(ch chan int) { ch <- 1 }
```

Missing 'go' keyword

# Concurrency in Go

## Deadlock detection

```
1 func main() {
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5 }
6
7 func send(ch chan int) { ch <- 1 }
```

Run program:

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

# Concurrency in Go

## Deadlock detection

- Go has a runtime deadlock detector, crashes if deadlock
- Deadlock if all goroutines are blocked
- Some packages (e.g. net for networking) **disables** it

```
1 import _ "net" // Load unused "net" package
2 func main() {
3     ch := make(chan int)
4     send(ch)
5     print(<-ch)
6 }
7 func send(ch chan int) { ch <- 1 }
```

# Concurrency in Go

## Deadlock detection

- Go has a runtime deadlock detector, crashes if deadlock
- Deadlock if all goroutines are blocked
- Some packages (e.g. net for networking) **disables** it

```

1 import _ "net" // Load unused
2 func main() {
3     ch := make(chan int)
4     send(ch)
5     print(<-ch)
6 }
7 func send(ch chan int) { ch <- 1 }

```

Add benign import

Deadlock **NOT** detected

# Abstracting Go with Behavioural Types

## Type syntax

$$\begin{aligned}
 \alpha &:= \bar{u} \mid u \mid \tau \\
 T, S &:= \alpha; T \mid T \oplus S \mid \&\{\alpha_i; T_i\}_{i \in I} \mid (T \mid S) \mid \mathbf{0} \\
 &\quad \mid (\text{new } a)T \mid \text{close } u; T \mid \mathbf{t}\langle \tilde{u} \rangle \mid \lfloor u \rfloor_k^n \mid u^* \\
 \mathbf{T} &:= \{\mathbf{t}\langle \tilde{y}_i \rangle = T_i\}_{i \in I} \text{ in } S
 \end{aligned}$$

- 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)

# Infer Behavioural Types from Go program

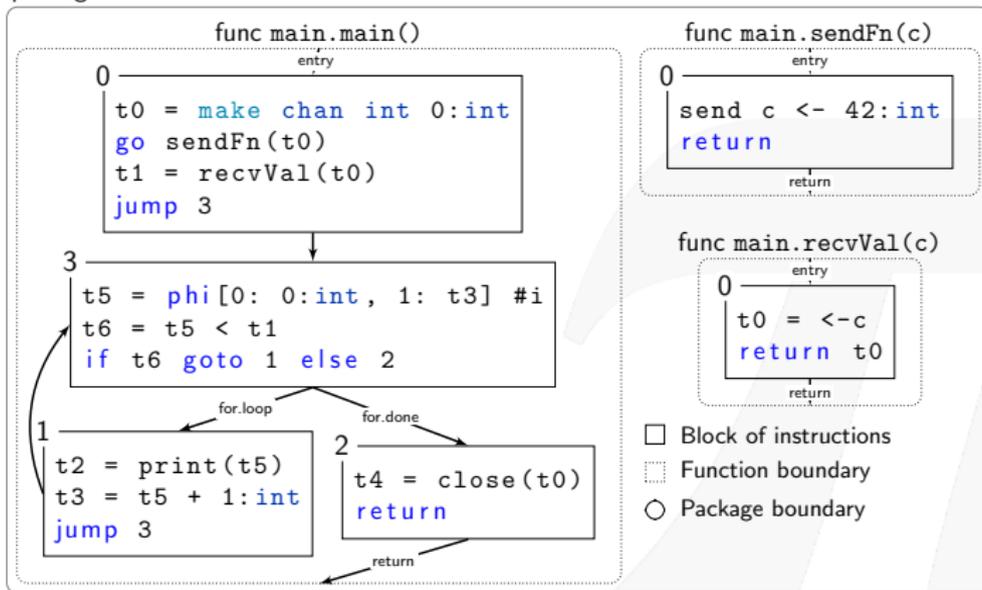
Input Go source code

```
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

Program in Static Single Assignment (SSA) form

package main



- Context-sensitive analysis to distinguish channel variables
- Skip over non-communication code

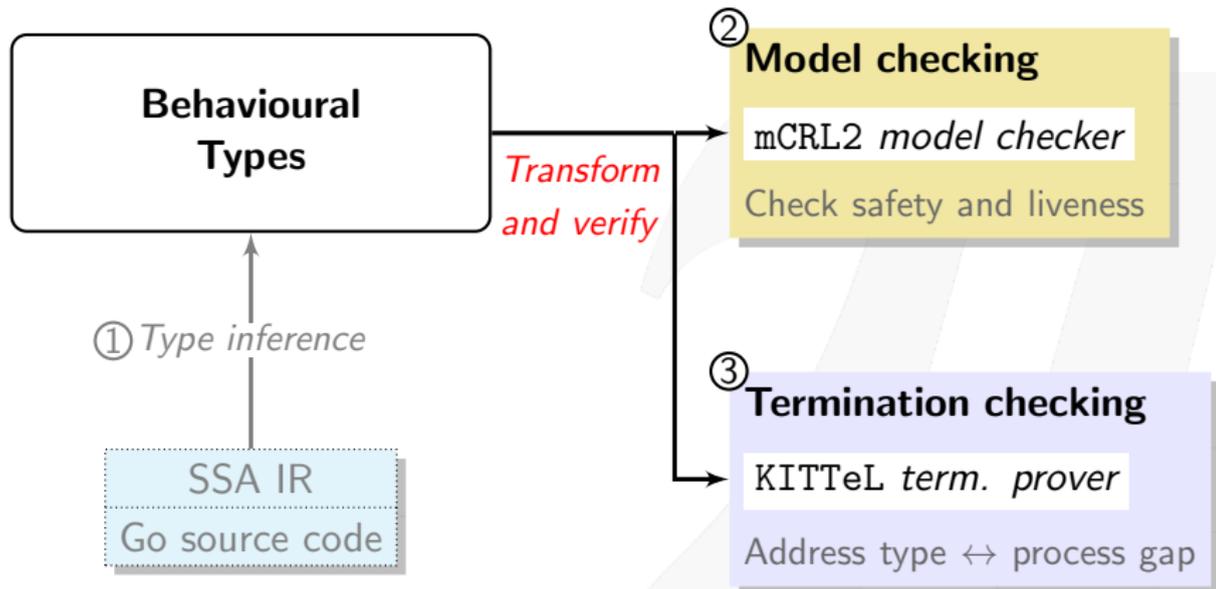
# Infer Behavioural Types from Go program

Types inferred from program

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

$$\begin{aligned}
 \text{main}() &= (\text{new } t0)(\text{sendFn}\langle t0 \rangle \mid \text{recvVal}\langle t0 \rangle; \text{main\_3}\langle t0 \rangle) \\
 \text{main\_1}(t0) &= \text{main\_3}\langle t0 \rangle \\
 \text{main\_2}(t0) &= \text{close } t0; 0 \\
 \text{main\_3}(t0) &= \text{main\_1}\langle t0 \rangle \oplus \text{main\_2}\langle t0 \rangle \\
 \text{sendFn}(c) &= \bar{c}; 0 \\
 \text{recvVal}(c) &= c; 0
 \end{aligned}$$

# Model checking behavioural types



# Model checking behavioural types

## Behavioural types as LTS model

1. Generate LTS **model** from type semantics
2. Generate  $\mu$ -calculus formulae for LTS describing **properties**
3. Check  $\text{LTS} \models$  formulae with model checker (e.g. mCRL2)

---

Properties of interest:

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

Constraints (on mCRL2 model checker):

- Finite control (no parallel composition in recursion)

Mi Go Liveness / Safety

$P \Downarrow a$

Barb  
[Milner 8  
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

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Barb  
[Milner 8  
Sangiorgi 92]

## Channel Safety

- ▶ Channel is closed at most once
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- ▶ Others raise an error and **crash**

$P$  is channel safe if  $P \xrightarrow{*} (\nu \bar{c}) Q$  and  $Q \Downarrow \text{close}(a)$

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

never closing

never send

a closed

# Migo Liveness / Safety

## ► Liveness

All reachable actions are eventually performed

$P$  is live if  $P \xrightarrow{*}_{(vc)} Q$

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

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

Reduction  
( $\tau$ )  
at  $a$

# Select



Time  
Out

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

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

$R_1 = a?$

# Select



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

Time  
out

if P is live  
 $P_1$  is live

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

$R_1 = a?$

# Select



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

Time  
out

if P is live  
 $P_1$  is live

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

$R_1 = a?$

$P_2$  is not  
live

$P_2 \mid R_2$  is

# Select



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

Time  
out

if P is live  
 $P_1$  is live

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

$R_1 = a?$

$P_2$  is not  
live  
 $P_2 | R_2$  is

Barb  $\downarrow \tilde{a}$

$\frac{\pi_i \downarrow a_i}{\text{select } \{\pi_i. P_i\} \downarrow \tilde{a}}$

$\frac{P \downarrow \tilde{a} \quad Q \downarrow \tilde{a}_i}{P | Q \downarrow [a_i]}$

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

# Model checking behavioural types

## Generating $\mu$ -calculus formulae (channel safety)

- Given an LTS model, generate formulae for safety properties
- Note: formulae are *model-specific*

### Property: Channel safety

$$\psi_s \stackrel{\text{def}}{=} \left( \bigwedge_{a \in \mathcal{A}} \downarrow a^* \right) \implies \neg(\downarrow \bar{a} \vee \downarrow \text{clo } a)$$

$\langle \alpha \rangle \phi$  is a modal operator, satisfied if:

There is a  $T'$  where  $T \xrightarrow{\alpha} T'$  such that formula  $\phi$  holds

# Model checking behavioural types

## Generating $\mu$ -calculus formulae (channel safety)

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$\langle \alpha \rangle \phi$  is a modal operator, satisfied if:

There is a  $T'$  where  $T \xrightarrow{\alpha} T'$  such that formula  $\phi$  holds

```

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

# Model checking behavioural types

## Generating $\mu$ -calculus formulae (liveness)

### Property: Liveness

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

### Property: Liveness (select)

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

- Liveness: sometimes known as *partial deadlock freedom*
- Program is live if  $(\psi_{I_a} \wedge \psi_{I_b})$  holds

# Model checking behavioural types

## Summary

1. Generate LTS **model** from type semantics
2. Generate  $\mu$ -calculus formulae for LTS describing **properties**
3. Check  $\text{LTS} \models$  formulae with model checker (e.g. mCRL2)

### Properties:

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

# Model checking behavioural types

## Termination checking with KITTeL

- Extracted types do not consider *data* in process
- Type liveness  $\neq$  program liveness
  - Especially when involving iteration
  - Check for loop termination
- Properties:
  - ✓ Global deadlock freedom
  - ✓ Channel safety (no send/`close` on closed channel)
  - ✓ Liveness (partial deadlock freedom)
  - ✓ Eventual reception

```

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

```

- Type: **Live**
- Program: **NOT** live

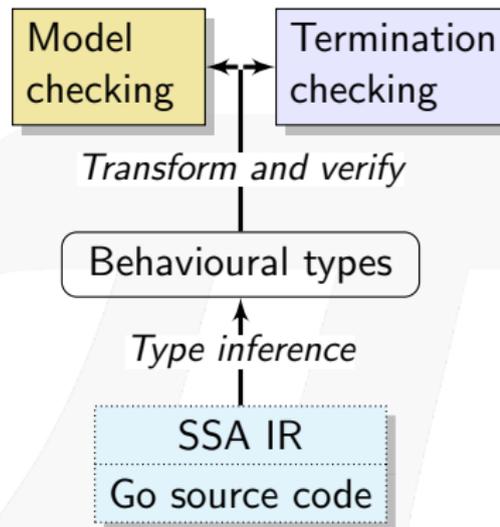
## Tool demo



# 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



## Future work

- Extend framework to support more properties
- Unlimited possibilities!
  - Different verification techniques
    - Godel-Checker model checking [ICSE'18] (this talk)
    - Gong type verifier [POPL'17]
    - Choreography synthesis [CC'15]
  - Different concurrency issues
    - Other synchronisation mechanisms
    - Race conditions



# Semantics of MiGo types

$$\begin{array}{c}
 \boxed{\text{SND}} \quad \bar{a}; T \xrightarrow{\bar{a}} T \quad \boxed{\text{RCV}} \quad a; T \xrightarrow{a} T \quad \boxed{\text{TAU}} \quad \tau; T \xrightarrow{\tau} T \\
 \\
 \boxed{\text{END}} \quad \text{close } a; T \xrightarrow{\text{clo } a} T \quad \boxed{\text{BUF}} \quad [a]_k^n \xrightarrow{\overline{\text{clo } a}} a^* \quad \boxed{\text{CLD}} \quad a^* \xrightarrow{a^*} a^* \\
 \\
 \boxed{\text{SEL}} \quad \frac{i \in \{1, 2\}}{T_1 \oplus T_2 \xrightarrow{\tau} T_i} \quad \boxed{\text{BRA}} \quad \frac{\alpha_j; T_j \xrightarrow{\alpha_j} T_j \quad j \in I}{\&\{\alpha_i; T_i\}_{i \in I} \xrightarrow{\alpha_j} T_j} \\
 \\
 \boxed{\text{PAR}} \quad \frac{T \xrightarrow{\alpha} T'}{T \mid S \xrightarrow{\alpha} T' \mid S} \quad \boxed{\text{SEQ}} \quad \frac{T \xrightarrow{\alpha} T'}{T; S \xrightarrow{\alpha} T'; S} \quad \boxed{\text{TERM}} \quad \mathbf{0}; S \xrightarrow{\tau} S \\
 \\
 \boxed{\text{COM}} \quad \frac{\alpha \in \{\bar{a}, a^*, a^\bullet\} \quad T \xrightarrow{\alpha} T' \quad S \xrightarrow{\beta} S' \quad \beta \in \{^\bullet a, a\}}{T \mid S \xrightarrow{\tau_a} T' \mid S'} \\
 \\
 \boxed{\text{EQ}} \quad \frac{T \equiv_\alpha T' \quad T \xrightarrow{\alpha} T''}{T' \xrightarrow{\alpha} T''} \quad \boxed{\text{DEF}} \quad \frac{T \{\bar{a}/\bar{x}\} \xrightarrow{\alpha} T' \quad \mathbf{t}(\bar{x}) = T}{\mathbf{t}(\bar{a}) \xrightarrow{\alpha} T'} \\
 \\
 \boxed{\text{CLOSE}} \quad \frac{T \xrightarrow{\text{clo } a} T' \quad S \xrightarrow{\overline{\text{clo } a}} S'}{T \mid S \xrightarrow{\tau} T' \mid S'} \quad \boxed{\text{IN}} \quad \frac{k < n}{[a]_k^n \xrightarrow{^\bullet a} [a]_{k+1}^n} \quad \boxed{\text{OUT}} \quad \frac{k \geq 1}{[a]_k^n \xrightarrow{a^\bullet} [a]_{k-1}^n}
 \end{array}$$

Figure: Semantics of types.

# Barb predicates for MiGo types

$$\begin{array}{c}
 \begin{array}{c}
 a; T \downarrow_a \quad \text{close } a; T \downarrow_{\text{clo } a} \\
 \bar{a}; T \downarrow_{\bar{a}} \quad a^* \downarrow_{a^*}
 \end{array}
 \quad
 \frac{\forall i \in \{1, \dots, n\} : \alpha_i \downarrow_{o_i}}{\&\{\alpha_i; T\}_{i \in \{1, \dots, n\}} \downarrow_{\{o_1 \dots o_n\}}}
 \\
 \\
 \frac{T \downarrow_o}{T; T' \downarrow_o}
 \quad
 \frac{T \downarrow_a \quad T' \downarrow_{\bar{a}} \text{ or } T' \downarrow_{a^*}}{T \mid T' \downarrow_{\tau_a}}
 \quad
 \frac{T \{\bar{a}/\bar{x}\} \downarrow_o \quad \mathbf{t}(\bar{x}) = T}{\mathbf{t}(\bar{a}) \downarrow_o}
 \\
 \\
 \frac{T \downarrow_a \quad \alpha_i \downarrow_{\bar{a}}}{T \mid \&\{\alpha_i; S_i\}_{i \in I} \downarrow_{\tau_a}}
 \quad
 \frac{T \downarrow_{\bar{a}} \text{ or } T \downarrow_{a^*} \quad \alpha_i \downarrow_a}{T \mid \&\{\alpha_i; S_i\}_{i \in I} \downarrow_{\tau_a}}
 \\
 \\
 \frac{k < n}{[a]_k^n \downarrow_{\bullet a}}
 \quad
 \frac{k \geq 1}{[a]_k^n \downarrow_{a \bullet}}
 \quad
 \frac{T \downarrow_{\bar{a}} \quad T' \downarrow_{\bullet a}}{T \mid T' \downarrow_{\tau_a}}
 \quad
 \frac{T \downarrow_{a \bullet} \quad \alpha_i \downarrow_a}{T \mid \&\{\alpha_i; S_i\}_{i \in I} \downarrow_{\tau_a}}
 \\
 \\
 \frac{T \downarrow_o}{T \mid T' \downarrow_o}
 \quad
 \frac{T \downarrow_o \quad a \notin \text{fn}(o)}{(\text{new}^n a); T \downarrow_o}
 \quad
 \frac{T \downarrow_o \quad T \equiv T'}{T \downarrow_o}
 \end{array}$$

Figure: Barb predicates for types.

# Model checking behavioural types

Generating  $\mu$ -calculus formulae (global deadlock freedom)

- Given an LTS model, generate formulae for safety properties
- Note: formulae are *model-specific*

Property: Global deadlock freedom

$$\psi_g \stackrel{\text{def}}{=} \left( \bigwedge_{a \in \mathcal{A}} \downarrow_a \vee \downarrow_{\bar{a}} \right) \implies \langle \mathbb{A} \rangle \text{true}$$

- $\langle \alpha \rangle \phi$  is a modal operator, satisfied if:  
There is a  $T'$  where  $T \xrightarrow{\alpha} T'$  such that formula  $\phi$  holds

# Model checking behavioural types

Generating  $\mu$ -calculus formulae (eventual reception)

Property: Eventual reception

$$\psi_e \stackrel{\text{def}}{=} \left( \bigwedge_{a \in \mathcal{A}} \downarrow_{a \bullet} \right) \implies \text{eventually} (\langle \tau_a \rangle \text{true})$$

- Applies only to buffered channels

# Eventually

## Eventually

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

- i.e.  $\phi$  holds in some reachable state