Behavioural Type-Based Static Verification Framework for GO

Julian Lange Nicholas Net
Bernardo Toninho Nobuko Yoshiida
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**


POPL 2008 Most Influential Paper Award

Kohei Honda, Nobuko Yoshida and Marco Carbone

Multiparty asynchronous session types
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.
End-to-End Switching Programme by DCC

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

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

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.

7. Generate exception report and send back to DCC.
End-to-End Switching Programme by DCC

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

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
7. Generate exception report and send back to DCC
A Session Type Provider

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

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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 in the refined protocol, up to premature termination.

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 auto-completion. For example, an instantiation of the in-built type provider for WSDL Web services [6] may look like
Selected Publications 2017/2018

- [CC’18] Rumyana Neykova, Raymond Hu, NY, Fahd Abdeljallal: Session Type Providers: Compile-time API Generation for Distributed Protocols with Interaction Refinements in F#.
Selected Publications 2017/2018

- [CC’18] Rumyana Neykova, Raymond Hu, NY, Fahd Abdeljallal: Session Type Providers: Compile-time API Generation for Distributed Protocols with Interaction Refinements in F#.
A static verification framework for message passing in Go using behavioural types

JANUARY 25, 2018

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!
The Go Programming Language

- Developed at Google for multicore programming
- Statically typed, natively compiled, **concurrent**
- Channel-based message passing for concurrency
- Used by major technology companies, e.g.

- docker
- kubernetes
- UBER
- NETFLIX
Go and concurrency

Approach and philosophy

*Do not communicate by sharing memory; Instead, share memory by communicating*
— Go language proverb

Encourages message passing over locking

- **Goroutines**: lightweight threads
- **Channels**: typed FIFO queues

Inspired by Hoare’s CSP/Process calculi
Overview Concurrency in Go Behavioural type inference Model checking behavioural types Termination checking Summary

Static verification framework for Go 🐱

Overview

Behavioural Types

Type inference

SSA IR

Go source code

Transform and verify

Model checking

mCRL2 model checker

Check safety and liveness

Termination checking

KITTeL termination prover

Address type ↔ program gap

Julien Lange, Nicholas Ng, Bernardo Toninho, Nobuko Yoshida
A Static Verification Framework for Message Passing in Go using Behavioural Types
Concurrent in Go 🧵

Goroutines

```go
func main() {
    ch := make(chan string)
    go send(ch)
    print(<-ch)
    close(ch)
}

func send(ch chan string) {
    ch <- "Hej ICSE!"
}
```

- **go** keyword + function call
  - Spawns function as goroutine
  - Runs in parallel to parent
Concurrent in Go 🐱

Channels

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

- 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
Concurrent in Go 🐘

Channels

```go
func main() {
    ch := make(chan string)
    go send(ch)
    print(<-ch)
    close(ch)
}

func send(ch chan string) {
    ch <- "Hej ICSE!"
}
```

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 <- "Hej ICSE!"`
10. `}`

- Send message thru channel
- Print message on screen

Output:

```
$ go run hello.go
Hej ICSE!
$ 
```
Concurrency in Go 🐒

Deadlock detection

Missing 'go' keyword

```
// import _ "net"

func main() {
    ch := make(chan string)
    send(ch) // Oops
    print(<-ch)
    close(ch)
}

func send(ch chan string) {
    ch <- "Hej ICSE"
}
```

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

Output:
```
$ go run deadlock.go
fatal error: all goroutines are asleep - deadlock!
$ 
```
Concurrent in Go

Deadlock detection

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

```go
// import _ "net"

func main() {
    ch := make(chan string)
    send(ch) // Oops
    print(<-ch)
    close(ch)
}

func send(ch chan string) {
    ch <- "Hej ICSE"
}
```
Concurrency in Go 🐘

Deadlock detection

```go
import _ "net" // unused

func main() {
    ch := make(chan string)
    send(ch) // Oops
    print(<-ch)
    close(ch)
}

func send(ch chan string) {
    ch <- "Hej ICSE"
}
```

Missing 'go' keyword

Import unused, unrelated package
Concurrency in Go

Deadlock detection

Missing 'go' keyword

```go
import _ "net" // unused

func main() {
    ch := make(chan string)
    send(ch) // Oops
    print(<-ch)
    close(ch)
}

func send(ch chan string) {
    ch <- "Hej ICSE"
}
```

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

Output:

```
$ go run deadlock2.go
Hangs: Deadlock NOT detected
```

Julien Lange, Nicholas Ng, Bernardo Toninho, Nobuko Yoshida
A Static Verification Framework for Message Passing in Go using Behavioural Types
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**

1. **Type inference**
   - SSA IR
   - Go source code

2. **Model checking**
   - mCRL2 *model checker*
   - Check safety and liveness

3. **Termination checking**
   - KITTeL *termination prover*
   - Address type ↔ program gap
Infer Behavioural Types from Go Program

Go source code

```go
func main() {
    ch := make(chan int)
    go send(ch)
    print(<-ch)
    close(ch)
}

func send(c chan int) {
    c <- 1
}
```

Behavioural Types

Types of CCS-like [Milner ’80]

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

Go-specific

- Close channel
- Select (guarded choice)
Infer Behavioural Types from Go Program

Go source code

```go
func main() {
    ch := make(chan int)
    go send(ch)
    print(<-ch)
    close(ch)
}

func send(c chan int) {
    c <- 1
}
```

Inferred Behavioural Types

```
main() = (new ch); (send(ch) | ch; close ch),

send(ch) = ~ch
```
Infer Behavioural Types from Go Program

Go source code

```go
func main() {
    ch := make(chan int)
    go send(ch)
    print(<-ch)
    close(ch)
}

func send(c chan int) {
    c <- 1
}
```

Inferred Behavioural Types

```
main() = (new ch);
spawn (send(ch) | ch; close ch),
receive send(ch) = ch
send
create channel
```
Infer Behavioural Types from Go Program

```go
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
```
Infer Behavioural Types from Go Program

package main

func main.main()

entry

0

t0 = make chan int 0: int
go sendFn(t0)
t1 = recvVal(t0)
jump 3

3

t5 = phi[0: 0: int, 1: t3] #
t6 = t5 < t1
if t6 goto 1 else 2

1
	2 = print(t5)
t3 = t5 + 1: int
jump 3

SSA representation of input program

func main.sendFn(c)

entry

0
send c <- 42: int
return

func main.recvVal(c)

entry

0

t0 = <-c
return t0

Only inspect communication primitives
Distinguish between unique channels

A Static Verification Framework for Message Passing in Go using Behavioural Types
Julien Lange, Nicholas Ng, Bernardo Toninho, Nobuko Yoshida
Model checking behavioural types

From behavioural types to model and property specification
Model checking behavioural types

\[ M \models \phi \]

- **LTS model**: inferred type + type semantics
- **Safety/liveness properties**: \( \mu \)-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 CCS semantics, i.e.

\[
\begin{align*}
\bar{a}; & T \xrightarrow{\bar{a}} T \\
T | S & \xrightarrow{\tau a} T' | S' \\
S & \xrightarrow{a} S'
\end{align*}
\]

- **Send** on channel \( a \)
- **Synchronise** on \( a \)
- **Receive** on channel \( a \)
Behavioural Types as \textit{LTS} model

Standard CCS semantics, i.e.

\[
\begin{align*}
\bar{a}; ~ T & \xrightarrow{a} ~ T \\
T \mid S & \xrightarrow{\tau a} ~ T' \mid S' \\
S \xrightarrow{a} & ~ S' \\
\end{align*}
\]

- Send on channel \(a\)
- Synchronise on \(a\)
- 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]
- \( \mu \)-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

\[ \bar{a} ; T \downarrow a \]

Ready to send

\[ T \downarrow a \] \quad \frac{T \downarrow \bar{a}}{T \mid T' \downarrow \tau a} \quad a; T \downarrow a \]

Ready to synchronise

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

\[ \bar{a}; T \downarrow_a \]

Ready to send

\[ T \downarrow \bar{a} \quad T' \downarrow a \]

Ready to synchronise

\[ T \mid T' \downarrow_{\tau_a} \]

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

Given

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

Express **safety/liveness properties**

- As $\mu$-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: Liveness (partial deadlock freedom)

\[ \bigwedge_{a \in \mathcal{A}} (\downarrow a \lor \downarrow \overline{a} \implies \text{eventually } (\langle \tau_a \rangle \text{true})) \]

\[ \mathcal{A} = \text{set of initialised channels} \]

If a channel is ready to receive or send, then \textbf{eventually} it can synchronise (\(\tau_a\))

(i.e. there’s corresponding send for \textit{receiver}/recv for \textit{sender})
Property: Liveness (partial deadlock freedom)

\[
\bigwedge_{a \in A} (\downarrow a \lor \downarrow \bar{a} \implies \text{eventually (} \langle \tau_a \rangle \text{true} \))
\]

where:

\[
\text{eventually (} \phi \text{)} \overset{\text{def}}{=} \mu y. (\phi \lor \langle A \rangle y)
\]

If a channel is ready to receive or send, then for some reachable state it can synchronise (\(\tau_a\))
Property: Liveness (partial deadlock freedom)

\[ \bigwedge_{a \in A} (\downarrow a \lor \downarrow \overline{a} \implies \text{eventually}(\langle \tau_a \rangle \text{true})) \]

```go
func main() {
    ch := make(chan int)
    go looper() // !!!
    <-ch // No matching send
}

func looper() {
    for {
    }
}
```

- Runtime detector: Hangs
- Our tool: NOT live
Property: Liveness (partial deadlock freedom)

\[ \bigwedge_{a \in A} (\downarrow a \vee \downarrow \overline{a} \implies \text{eventually } \langle \tau_a \rangle \text{true}) \]

```go
func main() {
    ch := make(chan int)
    go loopSend(ch)
    <-ch
}

func loopSend(ch chan int) {
    for i := 0; i < 10; i-- {
        // Does not terminate
    }
    ch <- 1
}
```

What about this one?

- Type: Live
- Program: NOT live

Needs additional guarantees
Termination checking

Addressing the program-type abstraction gap

1. Type inference

Behavioural Types

SSA IR

Go source code

2. Model checking

mCRL2 model checker

Check safety and liveness

3. Termination checking

KITTeL termination prover

Address type ↔ program 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

⇒ Check for loop termination

- If terminates, type liveness = program liveness

<table>
<thead>
<tr>
<th>Program terminates</th>
<th>Program does not terminate</th>
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<tbody>
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<td>Type live</td>
<td>✓  Program live</td>
</tr>
<tr>
<td>Type not live</td>
<td>✗  Program not live</td>
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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

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<td>✔</td>
<td>✔</td>
<td>3.5</td>
<td>996.6</td>
<td>996.6</td>
</tr>
</tbody>
</table>

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

\[ \bigwedge_{a \in A} (\downarrow a \lor \downarrow \overline{a} \implies \langle A \rangle \text{true}) \]

```go
import _ "net" // unused

func main() {
    ch := make(chan string)
    send(ch) // Oops
    print(<-ch)
    close(ch)
}

func send(ch chan string) {
    ch <- "Hej ICSE"
}
```

- Send (\(\downarrow_{\text{ch}}\text{: line 10}\))
- No synchronisation
- No more reduction
Property: Global deadlock freedom

\[ \bigwedge_{a \in A} (\downarrow a \lor \downarrow \bar{a} \implies \langle A \rangle \text{true}) \]

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

\( A = \text{set of all initialised channels} \quad \hat{A} = \text{set of all labels} \)
Property: Global deadlock freedom

\[ \bigwedge_{a \in \mathcal{A}} (\downarrow a \lor \downarrow \overline{a} \implies \langle \mathcal{A} \rangle \text{true}) \]

If a channel \( a \) is ready to \textit{receive} or \textit{send},
then there must be a \textbf{next state} (i.e. not stuck)

\( \mathcal{A} = \text{set of all initialised channels} \)
\( \mathfrak{A} = \text{set of all labels} \)

\( \implies \text{Ready receive/send} = \text{not end of program.} \)
Property: Channel safety

\[ \bigwedge_{a \in A} (\downarrow a^* \implies \neg(\downarrow a \lor \downarrow \text{clo } a)) \]

```go
def main() {
    ch := make(chan int)
    go func(ch chan int) {
        ch <- 1 // is ch closed?
    }(ch)
    close(ch)
    <-ch
}
```
Property: Channel safety

\[ \bigwedge_{a \in A} (\downarrow a^* \implies \neg (\downarrow \overline{a} \lor \downarrow \text{clo } a)) \]

```go
func main() {
    ch := make(chan int)
    go func(ch chan int) {
        ch <- 1 // is ch closed?
    }(ch)
    close(ch)
    <-ch
}
```

- \(\downarrow \text{clo } ch\) when `close(ch)`
- \(\downarrow \overline{ch}^*\) fires after closed
- Send (\(\downarrow \overline{ch}\): line 4)
Property: Channel safety

\[
\bigwedge_{a \in A} (\downarrow a^* \implies \neg (\downarrow \overline{a} \lor \downarrow \text{clo } a))
\]

Once a channel \( a \) is closed (\( a^* \)),
it will not be sent to, nor closed again (\( \text{clo } a \))
Property: Liveness (select)

\[ \bigwedge_{\tilde{a} \in \mathcal{P}(A)} (\downarrow \tilde{a} \implies \text{eventually} (\langle \{ \tau_a \mid a \in \tilde{a} \} \rangle \text{true})) \]

"If one of the channels in select is ready to receive or send, Then eventually it will synchronise (\(\tau_a\))

(i.e. there’s corresponding send for receiver/recv for sender)"
Property: Eventual reception

\[ \bigwedge_{a \in A} (\downarrow a \cdot \implies \text{eventually } (\langle \tau_a \rangle \text{true})) \]

“If an item is sent to a buffered channel \((a \cdot)\),
Then \textbf{eventually} it will be consumed/synchronised \((\tau_a)\)
(i.e. no orphan messages)
Behavioural Types for Go

Type syntax

$$\alpha := \overline{u} \mid u \mid \tau$$

$$T, S := \alpha; T \mid T \oplus S \mid \&\{\alpha_i; T_i\}_{i \in I} \mid (T \mid S) \mid 0$$

$$\mid (\text{new } a) T \mid \text{close } u; T \mid t\langle \tilde{u} \rangle \mid \lfloor u \rfloor^n_k \mid \text{buf}[u]_{\text{closed}}$$

$$T := \{t(\tilde{y}_i) = T_i\}_{i \in I} \text{ in } S$$

- 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)