Behavioural Type-Based Static Verification Framework for GO

Julien Lange

Nicholas Ng

Bernardo Toninho

Nobuko Yoshida

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

Mobility Research Group

session type

π-calculus, Session Types research at Imperial College

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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

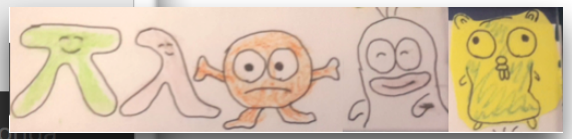
2018

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:

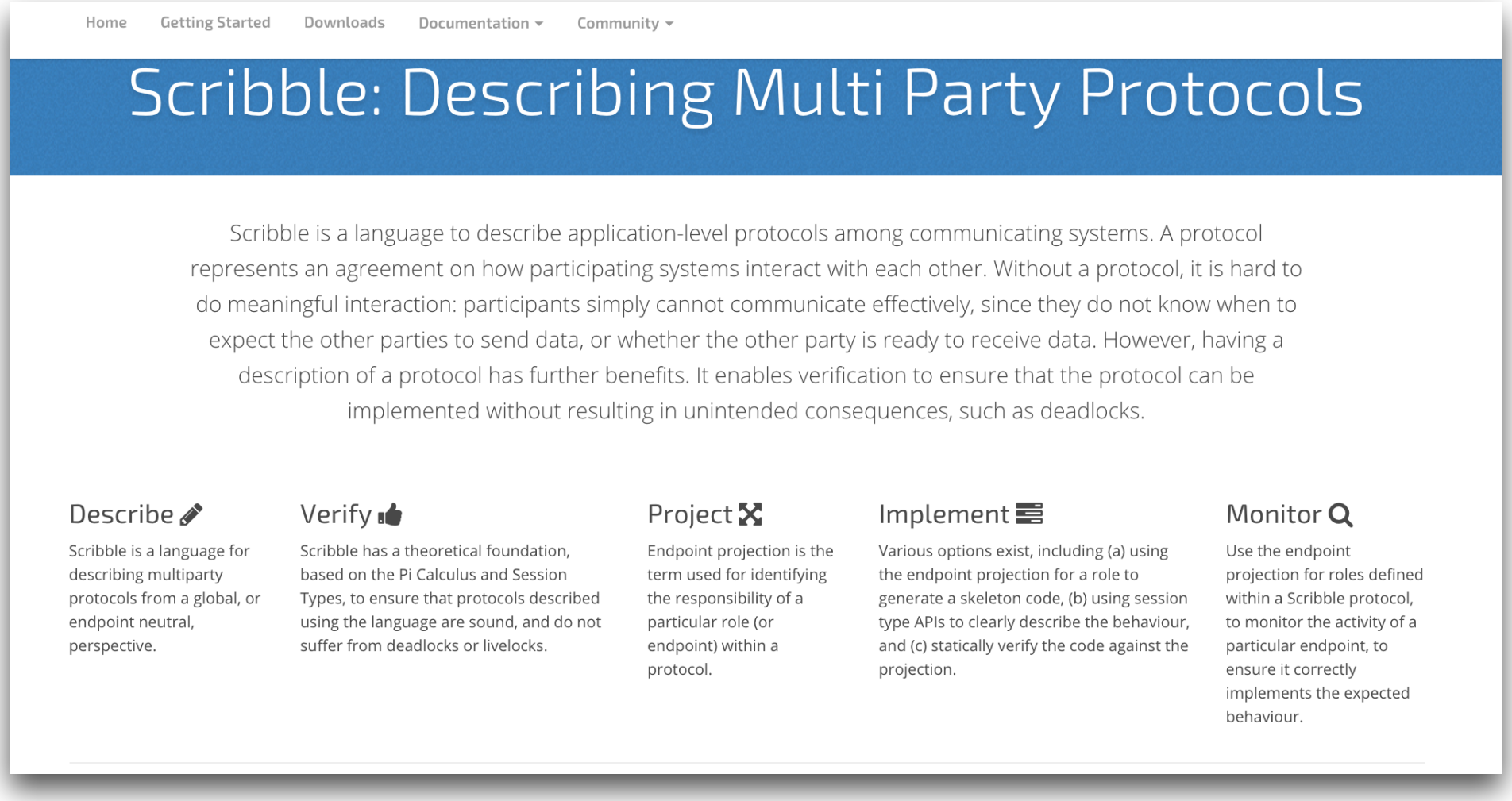
Assel ALTAYEVA

Juliana FRANCO

Eva GRAVERSEN

POPL 2008 MOST INFLUENTIAL PAPER AWARD

www.scribble.org



Online tool : http://scribble.doc.ic.ac.uk/

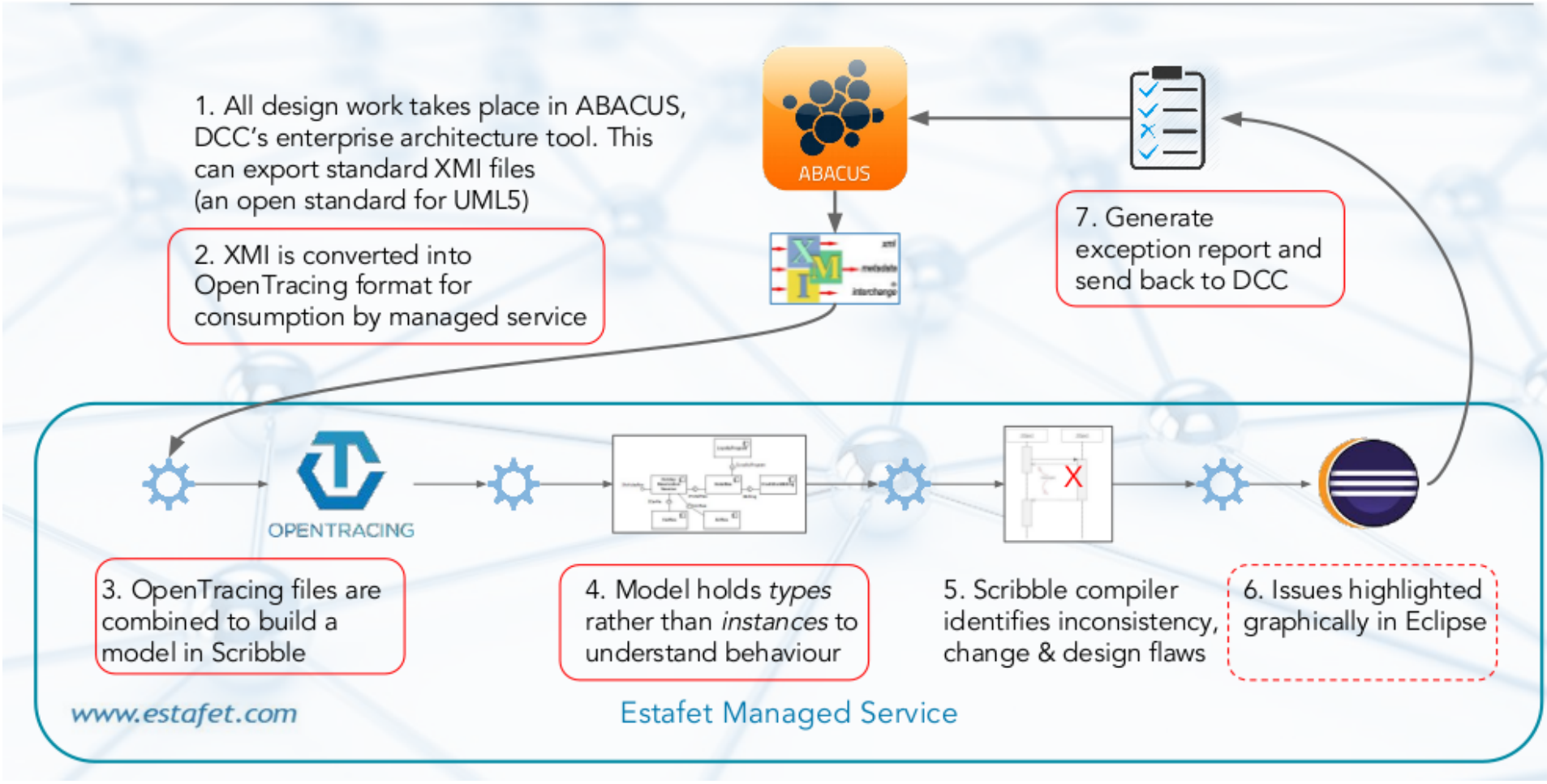
```
1  module examples;
2
3  global protocol HelloWorld(role Me, role World) {
4    hello() from Me to World;
5    choice at World {
6      goodMorning1() from World to Me;
7    } or {
8      goodMorning1() from World to Me;
9    }
10 }
11
```

Load a sample | Check | Protocol: examples.HelloWorld | Role: Me | Project | Generate Graph

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



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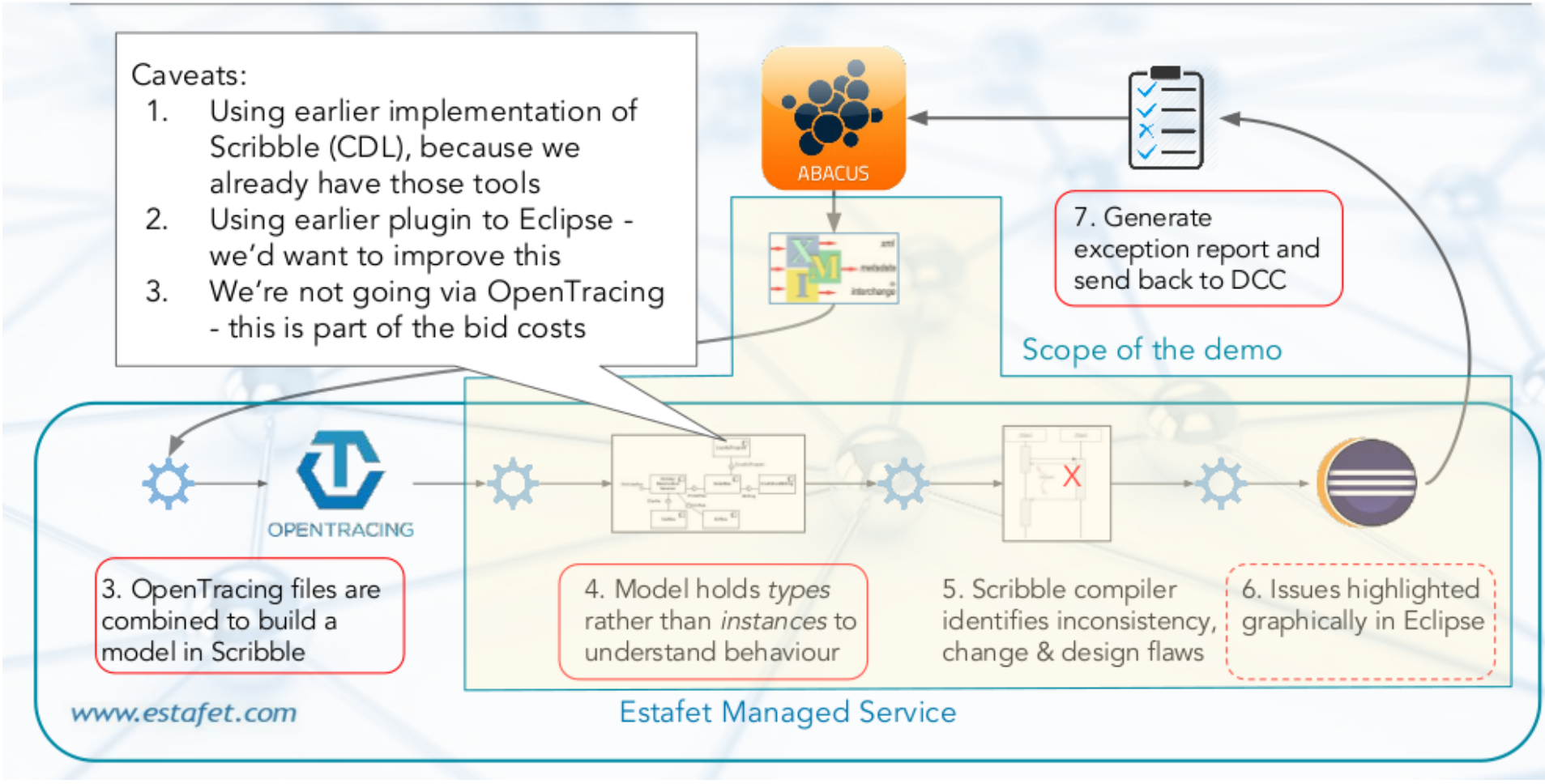

Interactions with Industries

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.

Nobuko Yoshida
Imperial College, London

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

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

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

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)

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#.
- **[FoSSaCS'18]** Bernardo Toninho, NY: Depending On Session Typed Process.
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- **[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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Imperial College London

News

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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

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

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!

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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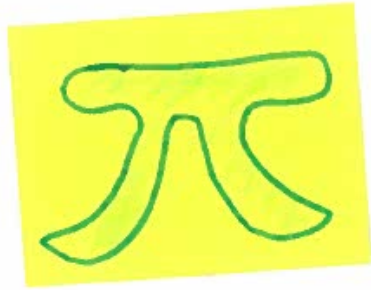

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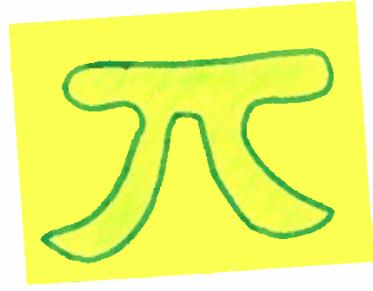

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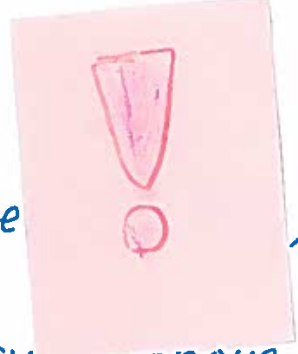

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186 ??

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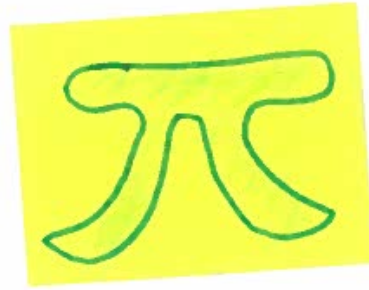

- Use behavioural types in process calculi
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- Dynamic channel creations, unbounded thread creation..., ...
- Scalable (synchronous/asynchronous) Modular, refinable

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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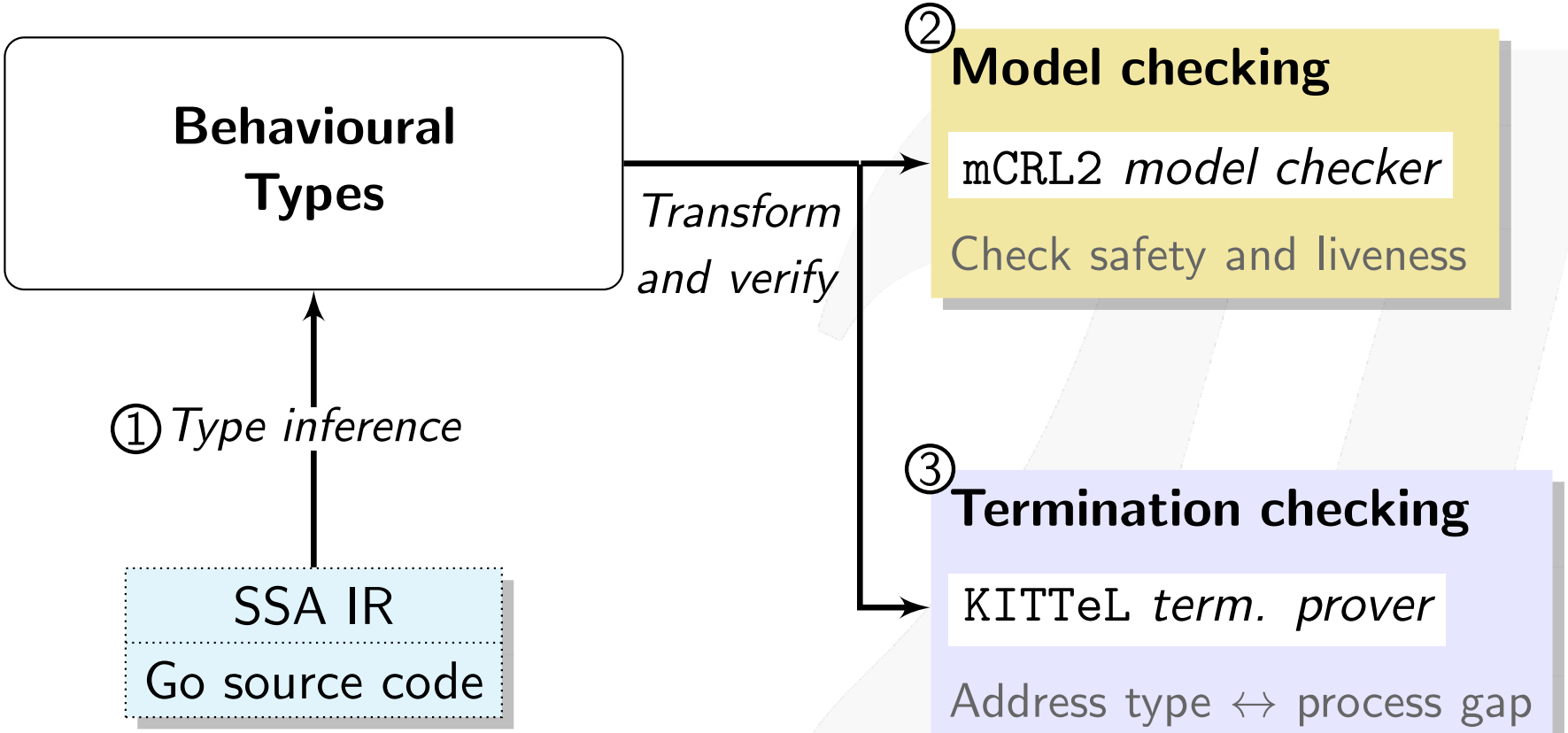
  - 3 Classes [POPL'17]
  - Termination Check

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() {
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  }
```

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

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

- 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)

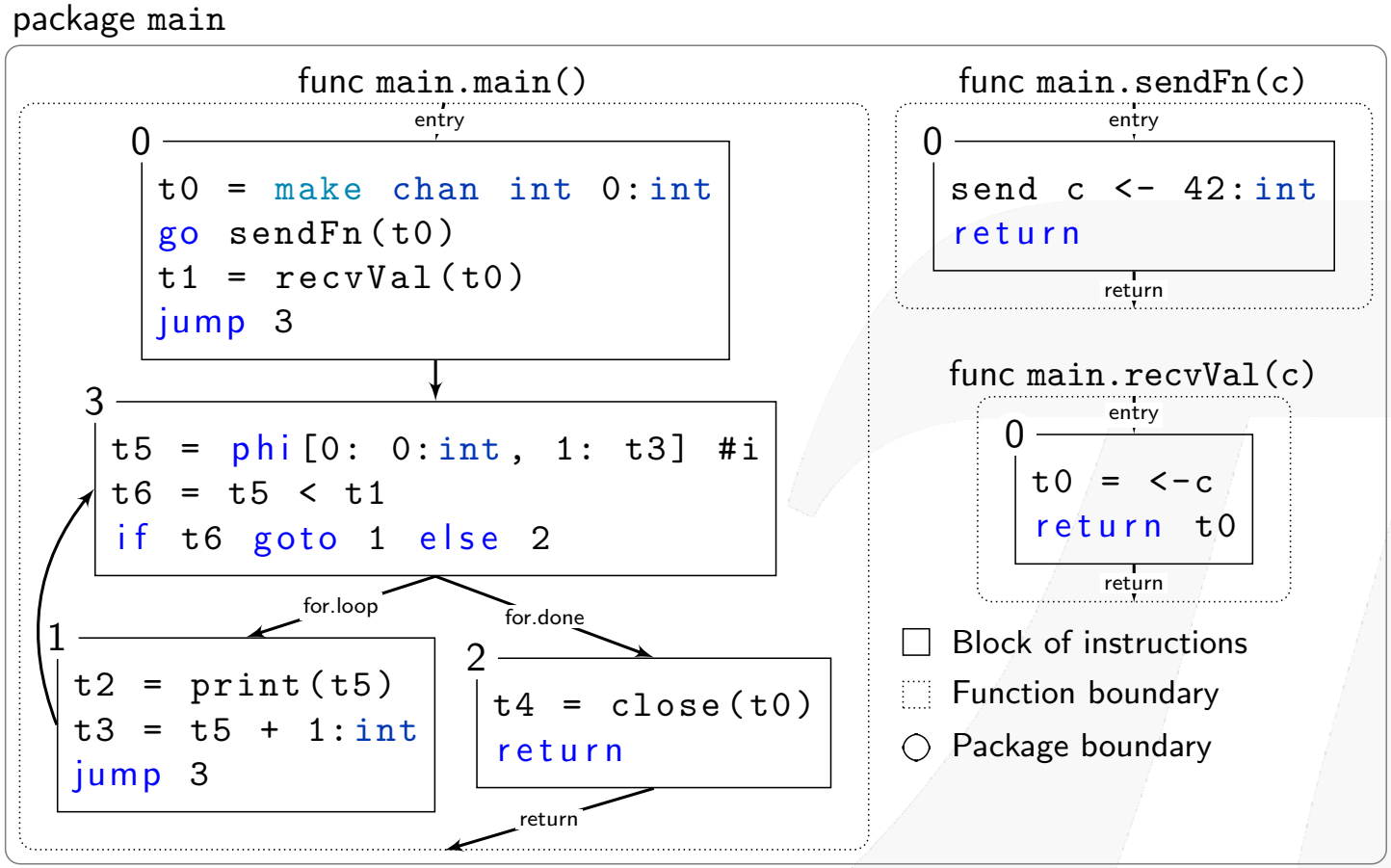
Infer Behavioural Types from Go program

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



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

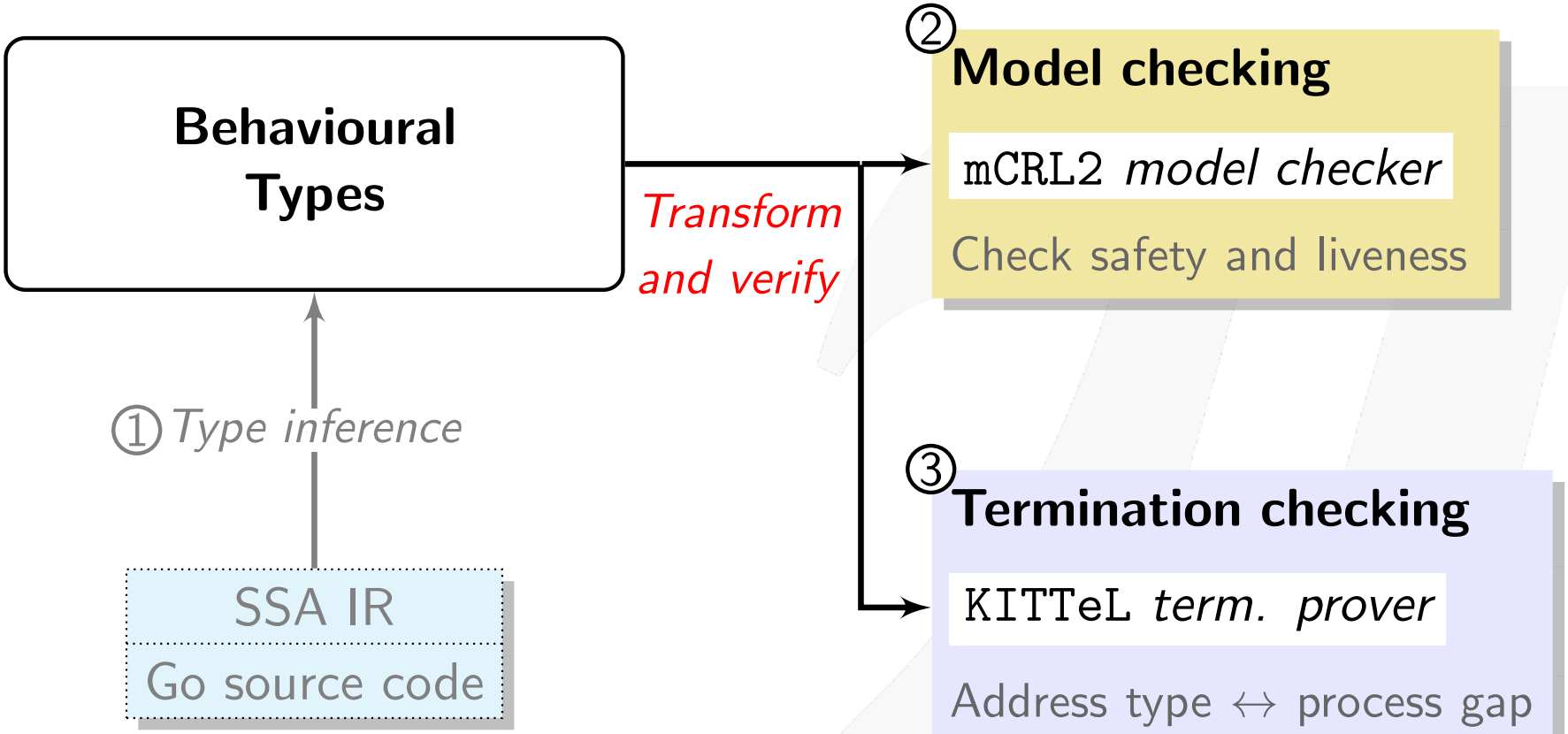
Infer Behavioural Types from Go program

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
```

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

Model checking behavioural types



Model checking behavioural types

Behavioural types as LTS model

1. Generate LTS **model** from type semantics
2. Generate μ-calculus formulae for LTS describing **properties**
3. Check 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)

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

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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

Model checking behavioural types

Generating μ-calculus formulae (channel safety)

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

Property: Channel safety

$$\psi_s \stackrel{\text{def}}{=} \left(\bigwedge_{a \in \mathcal{A}} \downarrow_{a^\star}\right) \implies \neg(\downarrow_{\overline{a}} \vee \downarrow_{\texttt{clo}\, a})$$

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

Model checking behavioural types

Generating μ-calculus formulae (channel safety)

Property: Channel safety

$$\psi_s \stackrel{\text{def}}{=} \left(\bigwedge_{a \in \mathcal{A}} \downarrow_{a^\star}\right) \implies \neg(\downarrow_{\overline{a}} \vee \downarrow_{\mathtt{clo}\, a})$$

$\langle\alpha\rangle\phi$ is a modal operator, satisfied if:
There is a T' where T $\xrightarrow{\alpha}$ T' such that formula ϕ 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 μ-calculus formulae (liveness)

Property: Liveness

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

Property: Liveness (select)

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

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

Model checking behavioural types

Summary

1. Generate LTS **model** from type semantics
2. Generate μ-calculus formulae for LTS describing **properties**
3. Check 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 }
```

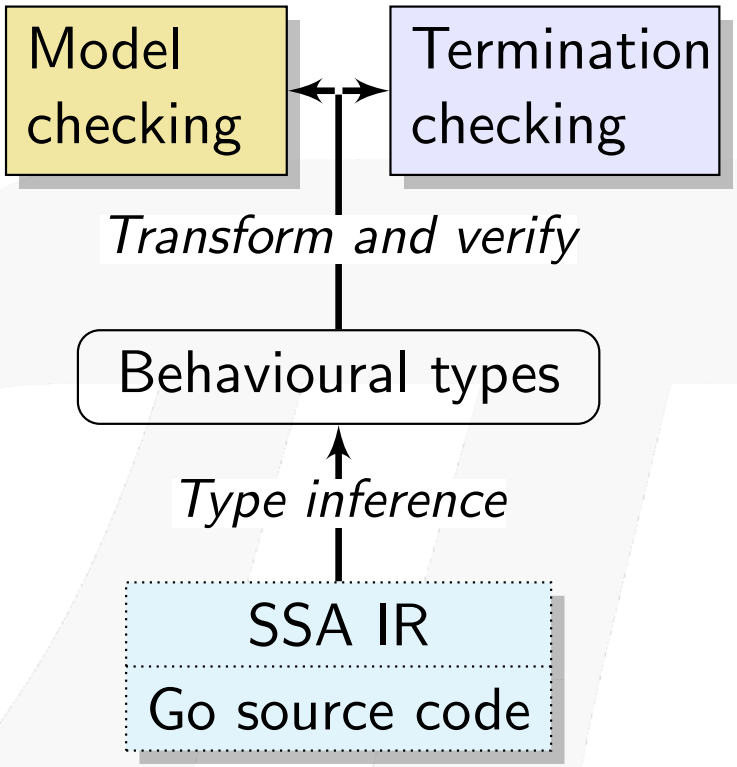
- Type: Live
- Program: NOT live

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

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

$$\text{END}\ \texttt{close}\ a; T \xrightarrow{\texttt{clo}\ a} T \qquad \text{BUF}\ \lfloor a \rfloor_k^n \xrightarrow{\overline{\texttt{clo}\ a}} a^\star \qquad \text{CLD}\ a^\star \xrightarrow{a^\star} a^\star$$

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

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

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

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

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

Figure: Semantics of types.

Barb predicates for MiGo types

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

$$\overline{a}; T \downarrow_{\overline{a}} \qquad a^\star \downarrow_{a^\star}$$

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

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

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

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

Figure: Barb predicates for types.

Model checking behavioural types

Generating μ-calculus formulae (global deadlock freedom)

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

Property: Global deadlock freedom

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

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

Model checking behavioural types

Generating μ-calculus formulae (eventual reception)

Property: Eventual reception

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

- 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. ϕ holds in some reachable state