Effpi

concurrent programming with dependent behavioural types

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ABCD Meeting
Imperial College London, 18th December 2018

The problem

Languages and toolkits for **message-passing concurrent programming** provide **intuitive high-level abstractions**

- e.g., actors, channels, processes (Akka, Erlang, Go, . . .)

. . . but **do not allow** to **verify code against behavioural specs**

- risks: **protocol violations**, **deadlocks**, **starvation**, . . .
- issues found **at run-time**, hence **expensive to fix**

The problem and our solution

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Our solution: **Effpi**, a toolkit for **strongly-typed concurrent programming** in **Dotty (a.k.a. Scala 3)**

- using **types as behavioural specifications**
- and **type-level model checking** to **verify code properties**

Example: payment service with auditing

A **payment service** should implement the following **specification**:

1. wait to receive a **payment request**
2. then, **either**:
   2.1 **reject** the payment, or
   2.2 report the payment to an **audit** service, and then **accept** it
3. continue from point 1

Example: payment service with auditing

Demo!

What is the Dotty / Scala 3 compiler saying?

```
found:     Out[ActorRef[Result], Accepted]

required:  Out[ActorRef[Result](pay.replyTo), Rejected]
           |
           Out[ActorRef[Audit[_]](aud), Audit[Pay(pay)]] >>:
             Out[ActorRef[Result](pay.replyTo), Accepted]
```

A λ-calculus with communication & concurrency

Example: a $pinger$ **process** sends a **communication channel** to a $ponger$ process, who uses the channel to reply `"Hello!"`

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Monadic encoding of the **higher-order** π**-calculus**

- λ-terms model **abstract processes**
- **Continuations** are expressed as λ-terms

How to type a process calculus

For typing, we use a context Γ with **channel types**. E.g.:

$$\Gamma = x : \mathsf{str} , y : \mathsf{c}^{\mathsf{o}}[\mathsf{str}]$$

Typing judgements are (partly) standard:

$$\Gamma \vdash \texttt{"Hello"} +\!\!+\, x : \mathsf{str}$$

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How do we **type communication?** E.g., if $\mathrm{t} = \mathbf{send}(y, x, \lambda\_.\mathbf{end})$

Classic approach: $\Gamma \vdash \mathrm{t} \ : \ \mathbf{proc}$ ("t is a well-typed process in Γ")

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Our approach: $\Gamma \;\vdash\; \mathrm{t} \;:\; \mathsf{T}$ (**“t behaves as T in Γ”**)

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Our approach: $\Gamma \vdash \mathrm{t} : \mathsf{T}$ (**"** t **behaves as** T **in** Γ**"**)

$\Gamma \vdash \mathsf{T} \leqslant \mathbf{proc}$ (**"** T **is a refined process type"**)

Behavioural types (inspired by π-calculus theory)

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If a term t has type T' above, we know that:

1. t is an **abstract process**. . .
2. that takes a string and a channel. . .
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Here's a term **with the same type** T', but **different behaviour**:

$$\lambda x.\lambda y.\big(\mathbf{let}\; z = \mathbf{chan}();\; \mathbf{send}(z, \texttt{"Hello!"}, \lambda\_.\mathbf{end})\big)$$

Behavioural types

This type is not very precise: e.g., it **does not track channel use**

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$\Pi(x{:}T_1)T_2$ where the return type T_2 can refer to x

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Types as behavioural specifications: examples

Types can provide **accurate behavioural specifications**. E.g.:

$$\mathsf{T}_1 \;=\; \Pi(x{:}\ldots)\,\Pi(y{:}\ldots)\,\mathbf{o}[\,y\,,\,x,\,\mathbf{i}[\,x,\,\Pi(z{:}\ldots)\,\mathbf{nil}\,]\,]$$

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- Give a **labelled semantics** to a type T
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Linear-time μ-calculus is **decidable** for T (Goltz'90; Esparza'97)

From theory to Dotty / Scala3

We **directly translate our types in Dotty / Scala 3**:

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$$\Downarrow$$

```
(x: String, y: OChan[String]) => Out[y.type, x.type, Nil]
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We implement our calculus as a **deeply-embedded DSL**. E.g.:

- calling `send(...)` yields an **object of type** `Out[...]`
- the object **describes** *(does not perform!)* **the desired output**
- the object is **interpreted** by a **runtime system**...
- ...that performs the actual output

From theory to Dotty / Scala3

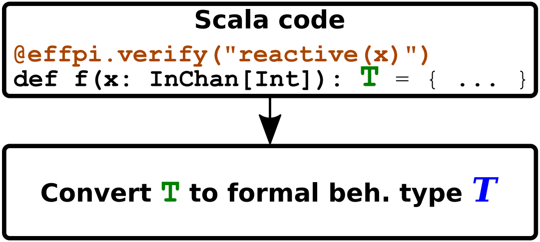
Demo!

Dotty compiler plugin: overview

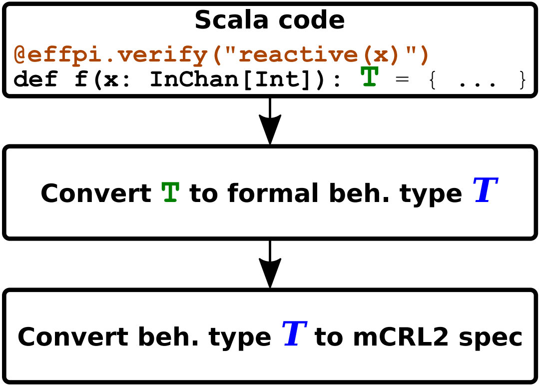
Scala code

```
@effpi.verify("reactive(x)")
def f(x: InChan[Int]): T = { ... }
```

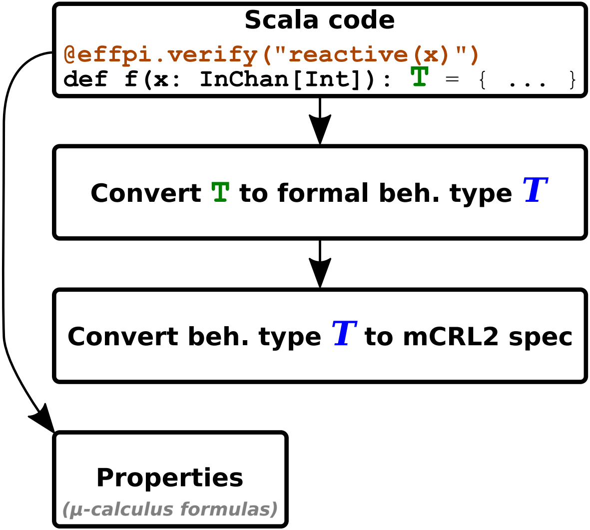
Dotty compiler plugin: overview



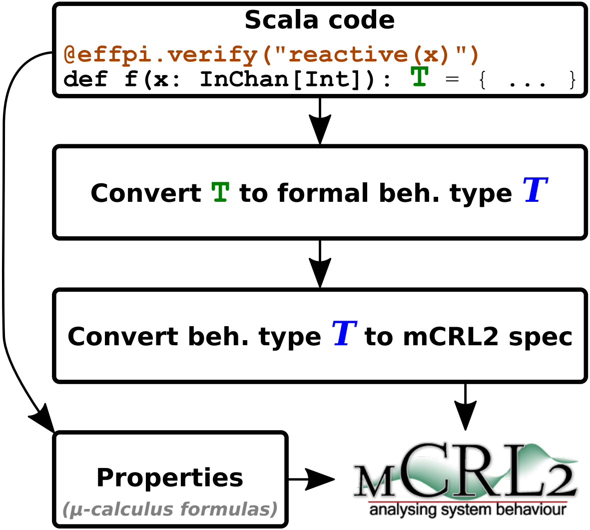
Dotty compiler plugin: overview



Dotty compiler plugin: overview



Dotty compiler plugin: overview



Interlude: a simplified actor-based DSL

We have discussed a **process-based calculus and DSL**. . .
. . . but the opening example was **actor-based!**

Interlude: a simplified actor-based DSL

We have discussed a **process-based calculus and DSL**. . .
. . . but the opening example was **actor-based!**

- An **actor is a process** with an **implicit input channel**
- The channel acts as a **FIFO mailbox** (as in the Akka framework)
- The actor DSL is **syntactic sugar on the process DSL**

Payoffs:

- we have **almost no actor-specific code**
- we **preserve the connection** to the underlying **theory**

How can we run our DSLs?

```scala
def payment(aud: ActorRef[Audit[_]]): Actor[Pay, _] =
  forever {
    read { pay: Pay =>
      if (pay.amount > 42000) {
        send(pay.replyTo, Rejected())
      } else {
        send(aud, Audit(pay)) >>
        send(pay.replyTo, Accepted())
      }
    }
  }
```

Naive approach: run each actor/process in a **dedicated thread**

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```

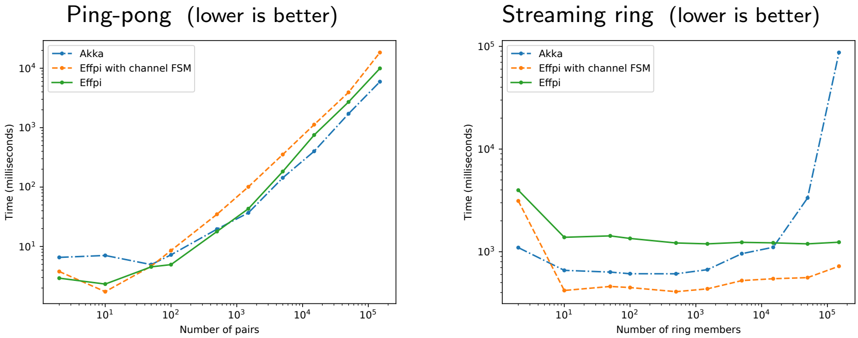
Naive approach: run each actor/process in a **dedicated thread**

As in our λ-calculus, **continuations are λ-terms** (closures)

For **better scalability**, we can:

- **schedule** closures to run on a **limited number of threads**
- **unschedule** closures that are **waiting for input**

Scalability and performance



The general performance is **not too far from Akka**

- main source of **overhead**: DSL interpretation

4 × Intel Core i7-4790 @ 3.60GHz; 16 GB RAM; Ubuntu 16.04; Java 1.8.0_181; Dotty 0.9.0-RC1; Scala 2.12.6; Akka 2.5.16

Conclusion

Effpi is an experimental framework for **strongly-typed concurrent programming** in **Dotty / Scala 3**

- with **process-based** and **actor-based APIs**
- with a **runtime** supporting **highly concurrent** applications
- with a **Dotty compiler plugin** to verify **type-level properties** via **model checking**, using `mCRL2`

Theoretical foundations:

- a **concurrent functional calculus**
- equipped with a **novel type system**, blending:
  - **behavioural types** (inspired by π-calculus theory)
  - **dependent function types** (inspired by Dotty / Scala 3)
- verify the **behaviour of processes** by **model checking types**

Appendix

Some references

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Verified mobile code

Modern distributed programming toolkits allow to send/receive **program thunks**, e.g. to:

- execute **user-supplied functions** (e.g., Amazon AWS Lambda)
- perform **remote updates of running code** (e.g., Erlang)

How can we **verify** that **the received thunks behave correctly?**

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E.g., if $\mathsf{T} = \Pi(x{:}\mathsf{c}^{\mathsf{io}}[\mathsf{int}])\mathsf{T}'$

- we know that the thunk **needs a channel** x carrying strings
- from T', we can deduce **if and how** the thunk uses x
- from T', we can ensure that the thunk is not a **forkbomb**