Effpi

concurrent programming with dependent behavioural types

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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**
- can vehicle **attacks**: e.g., data breaches, DoS

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

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Our approach: $\Gamma \vdash t : T$ (**“**t **behaves as** T **in** Γ**”**)

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

Behavioural types (inspired by π-calculus theory)

Some examples:

$$x : \mathsf{str}\,,\; y : \mathsf{c^o[str]} \;\vdash\; \mathbf{send}(y, x, \lambda\_.\mathbf{end}) \qquad : \; \mathsf{T}$$

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Yes — almost!

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**

$$T' = \mathsf{str} \to \mathsf{c}^{\circ}[\mathsf{str}] \to \mathbf{o}[\mathsf{c}^{\circ}[\mathsf{str}], \mathsf{str}, \mathbf{nil}]$$

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Introduce **dependent function types** (adapted from Dotty / Scala 3):

$\Pi(x{:}\mathsf{T}_1)\mathsf{T}_2$ 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.:

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

"Take x and y; use y send x; use x to receive some z; and terminate"

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Verification via **"type-level symbolic execution"**

- Give a **labelled semantics** to a type T
- **Model check** the **safety/liveness** properties of T
- Show how, if $\vdash \mathsf{t} : \mathsf{T}$ holds, then t "inherits" T's properties

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Model checking is **decidable** for T, but **not** for t (Goltz'90; Esparza'97)

From theory to Dotty / Scala3

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

$$\Pi(x{:}\mathsf{str})\ \Pi(y{:}\mathsf{c}^{\mathsf{o}}[\mathsf{str}])\ \mathbf{o}[y,\ x,\ \mathbf{nil}]$$

$$\Downarrow$$

```
(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!

A simplified actor-based DSL

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- 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?

```
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**

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**

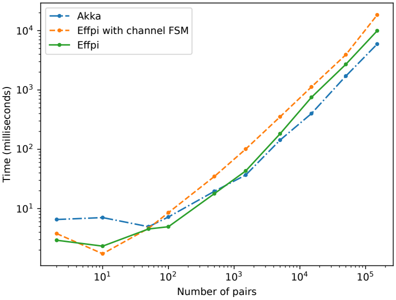
As in our λ-calculus, **continuations are λ-terms** (closures)

For **better scalability**, we can:

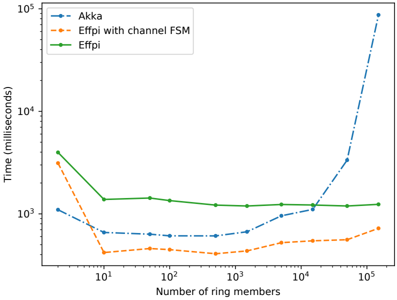
- **schedule** closures to run on a **limited number of threads**
- **unschedule** closures that are **waiting for input**

Scalability and performance

Ping-pong (lower is better)



Streaming ring (lower is better)



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

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**

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Work in progress:

- **Dotty compiler plugin** to verify **type-level properties** via **model checking**, using `mCRL2`

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)

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

- 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**