Compilation and Program Analysis (#13) : Advanced parallelism

Ludovic Henrio

Master 1, ENS de Lyon et Dpt Info, Lyon1

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What semantics for parallel programs

No big step semantics for parallelism

Denotational semantics difficult too because somehow big-step (see next slide)

Consequence: do small step semantics with interleaving between small steps

if P does $P \rightarrow P_1 \rightarrow P_2 \rightarrow ... \rightarrow P_n$ and Q does $Q_1 \rightarrow Q_1 \rightarrow Q_2 \rightarrow .. \rightarrow Q_n$ then $P||Q$ does the combination of the two. This is expressed by reordering processes ($P||Q \equiv Q||P$)and a simple rule:

$$\frac{P \rightarrow P'}{P||Q \rightarrow P'||Q}$$

This is most of the time sufficient but sometimes not enough, e.g. not directly adapted to weak memory models, no "true concurrency" of the form:

$$\frac{P \rightarrow P' \qquad Q \rightarrow Q'}{P||Q \rightarrow P'||Q'}$$

Cultural digression: About denotational semantics for parallelism

Recall: denotational semantics transforms a “program” into a “mathematical structure”
It looks like big-step but it depends on the structure generated. Generating something like a trace is possible too. Trace semantics exist but is not exactly denotational. However there are ways to get something more denotational, among our recent works:

- LAGC semantics with Reiner Hahnle, Einar Broch Johnsen et al.: kind of small-step denotational by “concretizing” the semantics at some points
- itrees / ctrees with Yannick Zakowski (and others): Generate a tree (coinductive) structure similar to a trace to take into account inputs, impure effects ... and non-determinism. Coq development for reasoning on languages and compilers.

Weak memory models

Question:What are the possible results (value of c) for running these two threads in parallel (initially a=b=c=0)?

```
a=1;                    ||    b=1;
if (b==0) then                if (a==0) then
  c++;                          c++;
```

Answer: It depends ... a lot, there are many ways to interpret the program

A memory model gives the semantics of memory accesses

Memory model – SC

Sequential Consistency :Each thread executes in its order, only interleaving occurs.

y = x	‖	x = 1
	‖	y = x

If initially $x = y = 0$, at the end $y = 1$.

Memory model – TSO

Total Store Ordering : E.g. x86, Writings are not observed immediately by other threads but locally it is consistent.

y = x	‖	x = 1
	‖	y = x

If initially $x = y = 0$, at the end $y = 0$ or $y = 1$.

Different weak memory models

- TSO is not sufficient to explain C, LLVM, ARM, etc.
- The hardware or the compiler may reorder memory operations according to rules. Typically “independent” read/writes.
- Even single threaded programs are subject to re-ordering.
- Powerful optimisations but difficult to verify/formalise.
- Examples : Promising, Pomsets with predicate transformers

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- Examples : Promising, Pomsets with predicate transformers

$$\text{y = x} \;\Big\|\; \begin{array}{l} \text{z = y} \\ \text{x = 1} \end{array}$$

With promising, at the end, z can be 0 or 1. Promising can express C++ weak memory model.

Different approaches to implement languages

Classical compilation: as seen in course

Source-to-source compilation: compiling to assembler is tedious and restricted to one architecture. Many source-to-source compilers, e.g. language-to-C / language-to-Java

Libraries / DSL: No translation at all. Relies on software engineering expertise to implement rich libraries DSLs while staying in the restriction of the host language

Next: 2 examples.

ProActive:

A Java API + Tools for Parallel, Distributed Computing

A uniform framework: **An Active Object pattern**
A formal model behind: **Determinism (POPL'04)**

- **Programming Model (Active Objects):**
- **Asynchronous Remote Invocations, Wait-By-Necessity**
- **Groups, Mobility, Components, Security, Fault-tolerance, Load balancing**
- **Environment:**
  - **XML Deployment Descriptors, File Transfers**
  - **Interfaced with:** `rsh, ssh, LSF, PBS, Globus, Jini, SUN Grid Engine`

Creating active objects

An object created with `A a = new A (obj, 7);`

can be turned into an active and remote object:

- **Object-based:**

```
a = (A)ProActive.turnActive (a, node);
```

- **Instantiation-based:**

```
A a = (A)ProActive.newActive(«A»,param,node);
```

`The "node" is the AO container.`

Remaining of the code unchanged → "Transparency"

Example 2: The Encore language approach

- A language with objects, futures, actors, etc. with a rich type system to optimise data access while preventing data-races.
- Many advanced features: Ownership types, parallel futures, forwarding, ...
- Compiled into C (source-to-source compilation)
- Relies on a specific C library, and an existing Actor library in C (pony) with a dedicated runtime (PonyRT) for final compilation and execution
- Tiny code example (observe the dedicated syntax):

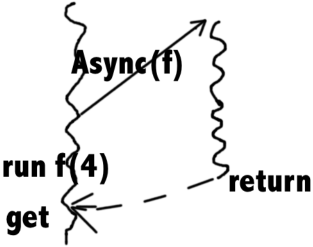
```
defrun() : void {
    let fut = service.provide()
        client =new Client()
    in {
      client.send(get fut);
    ...
    }
}
```

1. Generalities on semantics for parallelism
2. A brief introduction to weak memory models
3. Different approaches to implement languages
4. Dataflow explicit futures
   - Overview of future constructs
   - Preliminary studies
   - Dataflow explicit futures: principles
   - Semantics of flows and `forward*`
   - Implementation and evaluation of Flows in Encore
5. Conclusion

Back to miniwhile with futures – Example

```
int f (int x) (
  int z;
  z:=x+x
) return z

(
  int x,y;
  fut<int> t;
  t:=Async(f(3));
  y:=f(4);
  x:=get(t)
)
```



Back to miniwhile with futures with a complex example

```
fut<int> foo(int x) {
 fut<int> r ;
 r=async(bar(x+1));
 return r
}
int bar(int x) { skip; return x*x }
{
 fut<int> z ; int y ;
 fut<fut<int>> x;
 x:=async(foo(2));
 y:=get(get(x));
 y:=y+1;
 z:=get(x);
}
```

Is this program well-typed? What are the possible flows of execution?

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A few future constructs

- ABS

```
Fut<Int> f = o!add(2, 3); ❶
await f?; ❷
Int result = f.get; ❸
```

- Javascript **promises**

```
myFirstPromise.then((successMessage) => {
  console.log("Yay! " + successMessage);
});
```

- Akka: blocking or non-blocking

```
val future = actor ? msg // enabled by the “ask” import
val result = Await.result(future, timeout.duration).asInstanceOf[String]
```

- ProActive

```
Worker worker = (Worker) PAActiveObject.newActive(Worker.class.getName(),
                                null);//constructor arguments
Value v1 = worker.foo(); //v1 is a future
Value v2 = b.bar(v1); //v1 is passed as parameter
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Parametric type

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Classification of futures

	(a)synchronous	Typing	Data-flow synchronisation
ABS	Coop multithreading + synchronous	Parametric type	NO
ASP	Synchronous + WBN	Content	YES
Encore	Coop multithreading + synchronous + asynchronous (->)	Parametric type	NO
Akka	synchronous + asynchronous	future	NO
Javascript	Asynchronous	No	YES
Java	synchronous	Parametric type	NO

An example …

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Javascript	Asynchronous	No	YES
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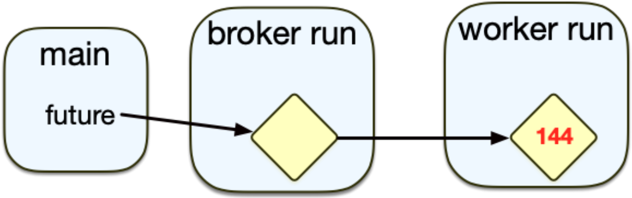
Implicit

An example …

Introducing the problem with Future Nesting: Naive Broker

```
class Broker:
 fun run(f: int -> int, x: int): Future[int]
  let worker: Worker = select_worker()
  return async(worker.run(f, x))

fun main(): unit
 let broker: Broker = get_broker()
 let future: Future[Future[int]] = async(broker.run(fibonacci, 12))
 let result: int = get(get(future))
```



Explicit Futures à la ABS

```
main () {
  alpha=new B();
  fut<fut<int>> x=alpha.foo(2);
  y=x.get.get;
  y=y+1;
  fut<fut<int>> z=alpha.foo_fut(x.get)
}
```

explicit synchronisation BUT I should know how many futures are imbricated … typing and synchronisation

```
class B()
…
fut<int> foo(int x) {
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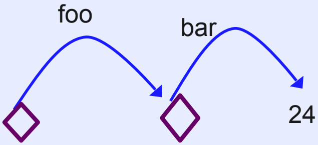

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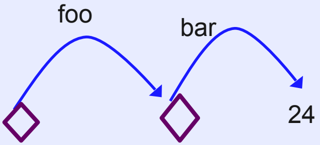


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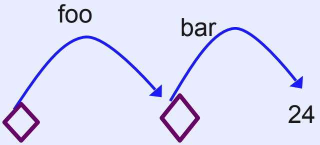


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  fut<int> r=ANOTHERAO.bar(t);
  return r;
}
```

Method duplicated
(typing + synchronisation)

In ASP: easier to write, erverything hidden

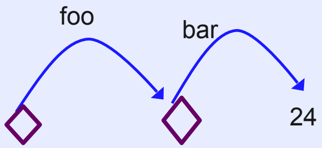
```
main () {
  alpha=new B();
  int x=alpha.foo(2);
  y=x+1;
  int z=alpha.foo(x)          }
```

transparent future access
(too simple?)

No useless synchronisation

```
class B()
...
int foo(int x) {
  int t=x+1;
  int r=ANOTHERAO.bar(t);
  return r;
}
```

A single method



No easy way to know that there might be a synchronisation here ... and **perhaps a deadlock**

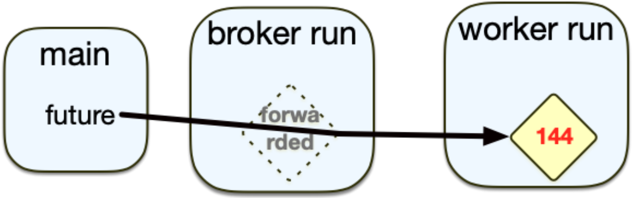
4 Dataflow explicit futures

- Overview of future constructs
- Preliminary studies
- Dataflow explicit futures: principles
- Semantics of flows and `forward*`
- Implementation and evaluation of Flows in Encore

Future Nesting: Forwarding Broker [Fernandez-Reyes et al. 2018]

```
class Broker:
 fun run(f: int -> int, x: int): int
  let worker: Worker = select_worker()
  forward(worker.run(f, x)) --Delegate resolution of current future

fun main(): unit
 let broker: Broker = get_broker()
 let future: Future[int] = async(broker.run(fibonacci, 12))
 let result: int = get(future)
```



Deadlock analysis for transparent futures (with Uni Bologna)

- Behavioural types allows detecting deadlock in ABS
- Extension to transparent first-class futures is not trivial
- Because of the **data-flow** nature: an **unbound** number of method behaviours may have to be **unfolded** at the synchronization point

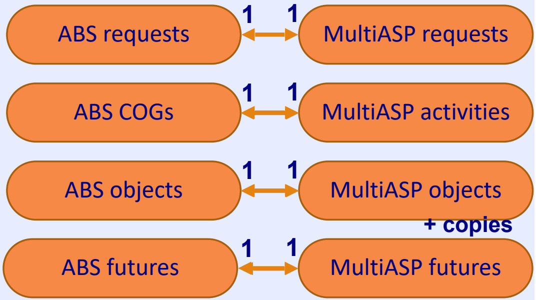
Terminal recursive functions

- We exhibit an analysis for transparent futures
  - Harder than for explicit futures
  - Even more useful as deadlocks are more difficult to find manually

ProActive backend for ABS
Using multi-active objects

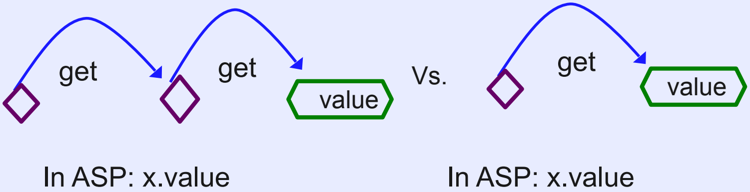
- Systematic translation of cooperative active objects into multi-threaded active objects
  - Instantiation on ABS and ProActive specifically
  - Faithful simulation
- Show the expressiveness of multiactive objects
- Show the differences btw active object languages

SHALLOW TRANSLATION



Futures: Dataflow synchronization ≠ explicit (control-flow) synchronization

- The translation simulates all possible ABS executions), *except:*
  - If a future value is a future (too strong restriction)
  - Not observable in MultiASP



- In ABS one can observe the end of a method execution, in ASP one can only observe the availability of some data

So, there are two kinds of futures: explicit or implicit

- Explicit
  - Control-flow synchronisation
  - Parametric type
  - Get (and await)
- Implicit
  - Data-flow synchronisation (wait-by-necessity)
  - No future type
  - No syntax for synchronisation

[ACM Comp Survey]

Well … **NOT EXACTLY!**

A summary of problems with classical explicit futures

Godot [Fernandez-Reyes et al 2019]

Godot: All the Benefits of Explicit and Implicit Futures, Fernandez-Reyes K., Clarke D., Henrio L., Broch Johnsen E., Wrigstad T., ECOOP 2019

- The Future Type Proliferation Problem leading to the nesting of future types in case of delegated calls
- The Future Reference Proliferation Problem referring to the possibly long chain of future references that has to be followed to reach the resolved future
- The Fulfilment Observation Problem referring to the fact that the events observed with data-flow and with control-flow synchronisations are not the same

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What makes the difference between future cnstructs?

Statically, typing makes the difference

Claim:

At runtime
Control-flow vs data-flow synchronisation

(and of course:

Synchronous vs asynchronous vs cooperative scheduling)

Idea: DeF – Explicit Futures with data-driven synchronisation

Type futures, but less strictly than in ABS

Flow<<>>

Static and Typing:

- No imbricated Flow<<>>
- It is always possible to put a A when a Flow<<A>> is expected

Runtime:

- get fetches future value until a non-future value is obtained

An example …

DeF: data-flow explicit futures

```
main () {
  alpha=new B();
  flow<<int>> x=alpha.foo(2);
  y=x.get;
  y=x+1;
  int z=alpha.foo(x)
}
```

No synchronisation here

explicit future access … but a SINGLE ACCESS!
Synchronisation visible but simple

```
class B()
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flow<<int>> foo(flow<<int>> x) {
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Typing of method a bit strange (avoidable if we change the typing rule for return)

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A single method that CAN receive a future
Code reuse

We declare that the method accepts a future as parameter and performs the **synchronisation if necessary** else the get does nothing

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One step further: terminal recursive asynchronous functions

In ABS

```
Int fact(Int n, Int r){
 Fut<Int>x; Int m;
 if (n==1) return r else {
   r = r*n;
   x = this.fact(n-1,r); m = await x;
   return m }}
```

Await? This method has to be unscheduled/rescheduled. **safe?**
Cooperative scheduling necessary

In ASP

```
Int fact(Int n, Int r){
 Int y;
 if (n == 1) return r else {
   r = r*n;
   y = this.fact(n-1,r); return y }}
```

Similar to sequential code, no synchronisation (**except if n is a future)**

In DeF

```
Fut«Int» fact(Int n, Int r) {
 Fut«Int» y;
 if (n == 1) return r   else {
   r = r*n;
   y = this.fact(n-1,r);  return y }}
```

Body as expected (no synchronisation)
No coop scheduling
No deleg

An implementation in Encore – explicit futures

```
active class B
 def bar(t: int): int
  t * 2
 end

 def foo(x: int): Fut[int]
  val t = x + 1
  val beta = new B()
  beta!bar(t)
 end

 --we need this function as foo
 --cannot take both fut and int
 def foo_fut(x: Fut[int]): Fut[int]
  this.foo(get(x))
 end
end

active class Main
 def main(): unit
  val alpha = new B()
  val x: Fut[Fut[int]] = alpha!foo(1)
  val y: int = get(get(x)) + 1
  val z: Fut[Fut[int]] = alpha!foo_fut(get(x))
  println(get(get(z))) --10
 end
end
```

An implementation in Encore – dataflow futures (flow)

```
active class B
  def bar(t: int): int
    t * 2
  end

  def foo(x: Flow[int]): Flow[int]
    val t = get*(x) + 1
    val beta = new B()
    beta!!bar(t)
  end
end
```

```
active class Main
  def main(): unit
    val alpha = new B()
    val x: Flow[int] = alpha!!foo(1)
           --this lifts 1 from int to Flow[int]
    var y: int = get*(x) + 1
    val z: Flow[int] = alpha!!foo(x)
    println(get*(z)) --10
  end
end
```

Synchronization (why control and data flow?)

- Explicit futures

  `Future[Future[int]]` ⇒ `get(get())`

  - Synchronization resolved by end of computation (control-flow)

- Dataflow explicit futures

  `Flow[int]` ⇒ `get*()`

  - Synchronization resolved by availability of data (dataflow)

4 Dataflow explicit futures

- Overview of future constructs
- Preliminary studies
- Dataflow explicit futures: principles
- **Semantics of flows and `forward*`**
- Implementation and evaluation of Flows in Encore

The Godot Hypothesis

The Godot Hypothesis

When working with dataflow explicit futures, `forward*` is equivalent to `return`.

Outline:

1. Semantics of `return`
2. Introduction to bisimulation
3. Semantics of `forward*` and equivalence proof

Flowing Broker – semantics

```
class Broker:
 fun run(f: int -> int, x: int):
    Flow[int]
   let worker = select_worker()
   return async*(worker.run(f, x))

fun main(): unit
 let broker: Broker = get_broker()
 let flow: Flow[int] = async*(
   broker.run(fibonacci, 12)
 )
 let result: int = get*(flow)
 println(result)
```

`flow`$_0$ (main thread)

computing main()

Flowing Broker – semantics

```
class Broker:
 fun run(f: int -> int, x: int):
    Flow[int]
  let worker = select_worker()
  return async*(worker.run(f, x))

fun main(): unit
 let broker: Broker = get_broker()
 let flow: Flow[int] = async*(
  broker.run(fibonacci, 12)
 )
 let result: int = get*(flow)
 println(result)
```

`flow`$_0$ (main thread)

computing main()

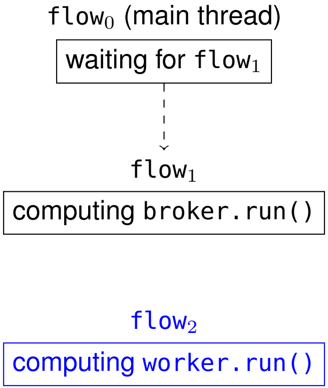
`flow`$_1$

computing `broker.run()`

Flowing Broker – semantics

```
class Broker:
 fun run(f: int -> int, x: int):
    Flow[int]
  let worker = select_worker()
  return async∗(worker.run(f, x))

fun main(): unit
 let broker: Broker = get_broker()
 let flow: Flow[int] = async∗(
  broker.run(fibonacci, 12)
 )
 let result: int = get∗(flow)
 println(result)
```



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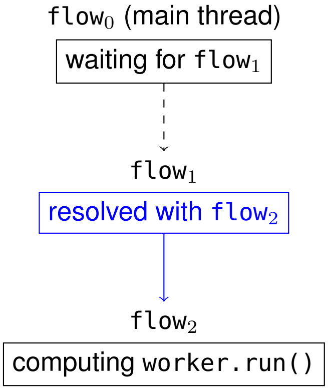
```



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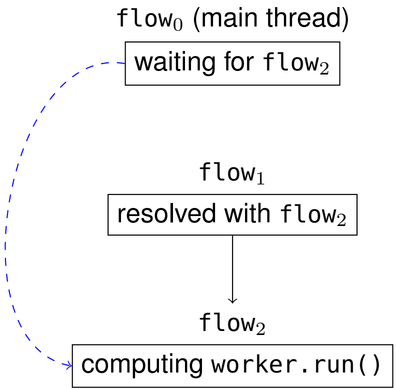

Flowing Broker – semantics

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class Broker:
  fun run(f: int -> int, x: int):
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  println(result)
```
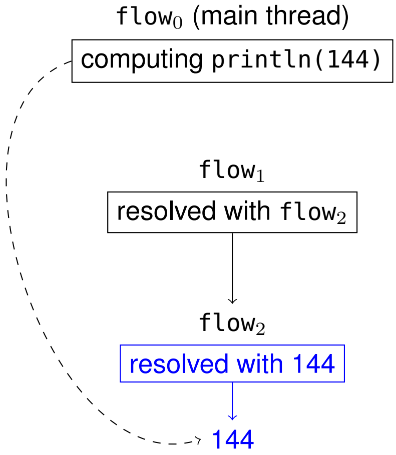



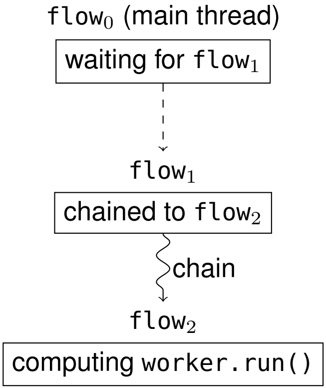
Forward

Forward is a construct that does a shortcut (exists in Encore and illustrated above).

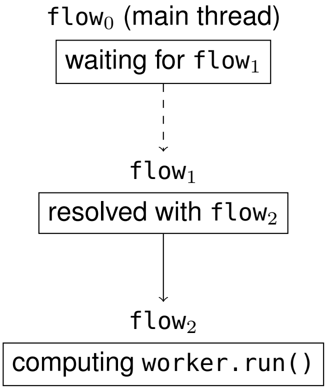
In With dataflow futures it works more or less the same (see next slides).

Semantics with forward*

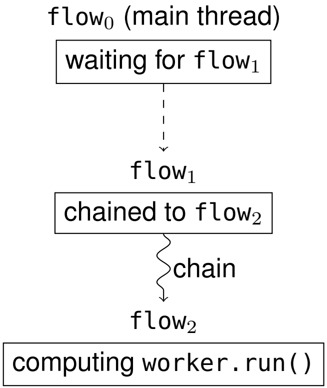
```
class Broker:
  fun run(f: int -> int, x: int):
      Flow[int]
    let worker = select_worker()
    forward* async*(worker.run(f, x))

fun main(): unit
  let broker: Broker = get_broker()
  let flow: Flow[int] = async*(
    broker.run(fibonacci, 12)
  )
  let result: int = get*(flow)
  println(result)
```



Flow/return semantics



forward* semantics



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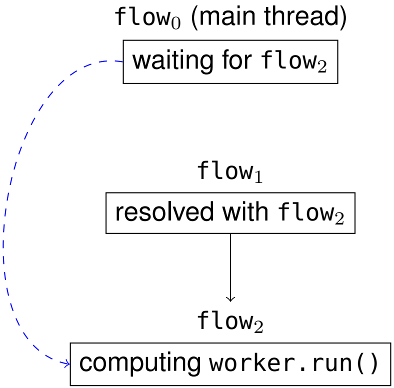

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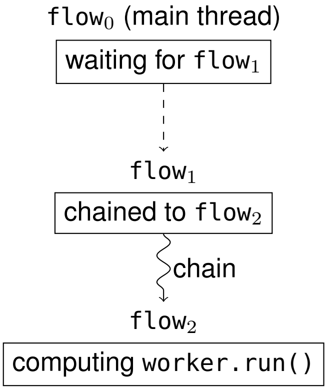

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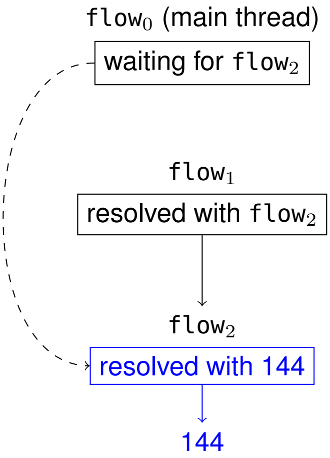

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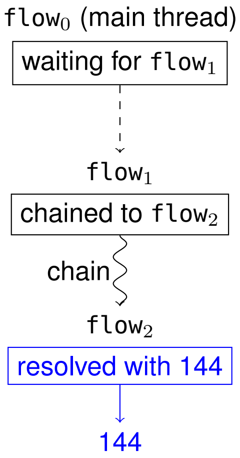
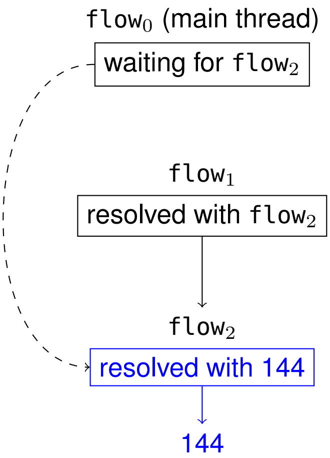
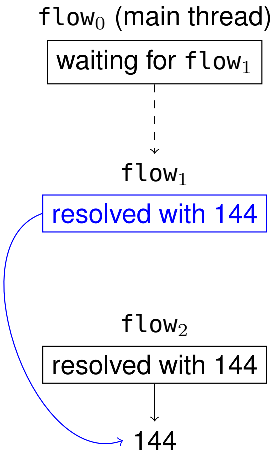


Flow/return semantics



forward* semantics



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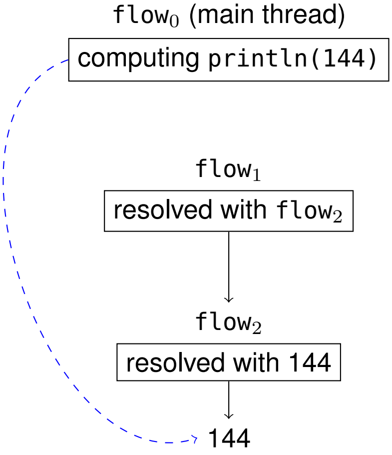
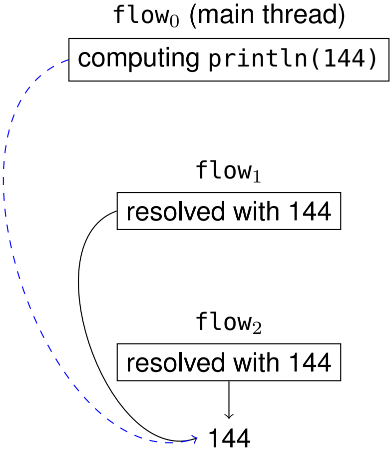


forward* semantics



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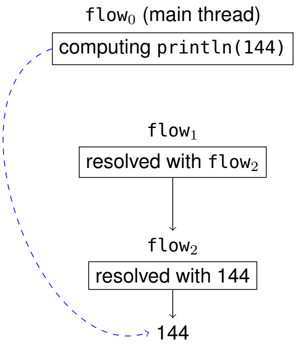
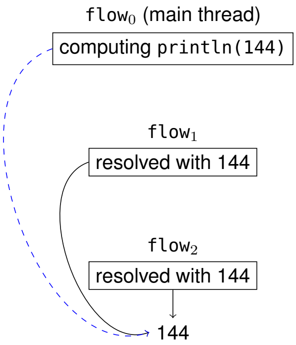


forward* semantics

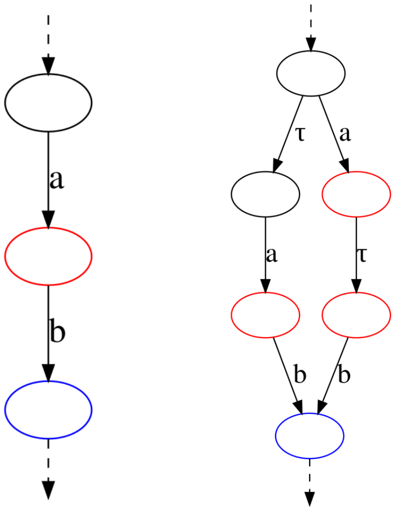


Lemma: preservation of sequences

For all sequence of flows in a program, there is a sequence of flows with the same source and same destination in this program with `forward*` replaced with `return`

Branching bisimulation

- Tool to compare semantics of transition systems based on a relation $\mathcal{R}$ between states
- Taus are non-observable internal events
- Strong > branching > weak bisimulation



Branching bisimulation (briefly)

Weak: If $s \mathcal{R} s'$ and $s \xrightarrow{\alpha} t$, there has to exist t' such that $s' \xrightarrow{\tau}^* \xrightarrow{\alpha} \xrightarrow{\tau}^* t'$ and $t \mathcal{R} t'$.

Branching: Doing a tau stays in the same equivalence class.

No branching bisimulation here, just a weak bisimulation.

`return` and `forward*`

- We prove a branching bisimulation. Are considered τ transitions:
  - Updates of the chains in the `forward*` case
  - Updates of the `gets` in the `return` case

Theorem

When working with dataflow explicit futures, `forward*` and `return` are *observably* equivalent.

Semantic rules

ASSIGN
$$\frac{[\![e]\!]_{a+\ell} = w \qquad (a+\ell)[x \mapsto w] = a' + \ell'}{a \rangle F\ f(\{\ell \mid x = e\,;s\}\#\overline{q}) \to a' \rangle F\ f(\{\ell' \mid s\}\#\overline{q})}$$

INVK-ASYNC
$$\frac{[\![\overline{v}]\!]_{a+\ell} = \overline{w} \qquad \text{bind}(m,\overline{w}) = q' \qquad f' \ \text{fresh}}{a \rangle F\ f(\{\ell \mid x = !\mathtt{m}(\overline{v})\,;s\}\#\overline{q}) \to a \rangle F\ f(\{\ell \mid x = f'\,;s\}\#\overline{q})\ f'(q')}$$

INVK-SYNC
$$\frac{[\![\overline{v}]\!]_{a+\ell} = \overline{w} \qquad \text{bind}(m,\overline{w}) = q'}{a \rangle F\ f(\{\ell \mid x = \mathtt{m}(\overline{v})\,;s\}\#\overline{q}) \to a \rangle F\ f(q'\#\{\ell \mid x = \mathtt{m}(\overline{v})\,;s\}\#\overline{q})}$$

RETURN-ASYNC
$$\frac{[\![v]\!]_{a+\ell} = w}{a \rangle F\ f(\{\ell \mid \mathtt{return}\ v\,;s\}) \to a \rangle F\ f(w)}$$

RETURN-SYNC
$$\frac{[\![v]\!]_{a+\ell'} = w}{a \rangle F\ f(\{\ell' \mid \mathtt{return}\ v\,;s\}\#\{\ell \mid x = \mathtt{m}(\overline{v})\,;s'\}\#\overline{q}) \to a \rangle F\ f(\{\ell \mid x = w\,;s'\}\#\overline{q})}$$

GET-FUTURE
$$\frac{[\![v]\!]_{a+\ell} = f'}{a \rangle F\ f(\{\ell \mid y = \mathtt{get*}\ v\,;s\}\#\overline{q})\ f'(w') \to a \rangle F\ f(\{\ell \mid y = \mathtt{get*}\ w'\,;s\}\#\overline{q})\ f'(w')}$$

GET-DATA
$$\frac{[\![v]\!]_{a+\ell} = b}{a \rangle F\ f(\{\ell \mid y = \mathtt{get*}\ v\,;s\}\#\overline{q}) \to a \rangle F\ f(\{\ell \mid y = b\,;s\}\#\overline{q})}$$

Additional rules for `forward*`

FORWARD-ASYNC

$$\frac{[\![v]\!]_{a+\ell} = f'}{a \rangle F\ f(\{\ell \mid \texttt{forward*}\ v\ ; s\}) \to a \rangle F\ f(\texttt{chain}\ f')}$$

FORWARD-SYNC

$$\frac{[\![v]\!]_{a+\ell} = w}{a \rangle F\ f(\{\ell \mid \texttt{forward*}\ v\ ; s\}\#q\#\overline{q}) \to a \rangle F\ f(\{\ell \mid \texttt{return}\ w\ ; s\}\#q\#\overline{q})}$$

FORWARD-DATA

$$\frac{[\![v]\!]_{a+\ell} = b}{a \rangle F\ f(\{\ell \mid \texttt{forward*}\ v\ ; s\}) \to a \rangle F\ f(b)}$$

CHAIN-UPDATE

$$\frac{}{a \rangle F\ f(\texttt{chain}\ f')\ f'(w) \to a \rangle F\ f(w)\ f'(w)}$$

4 Dataflow explicit futures

- Overview of future constructs
- Preliminary studies
- Dataflow explicit futures: principles
- Semantics of flows and `forward*`
- Implementation and evaluation of Flows in Encore

Implementing flows

Early attempt: flows from futures

- Attempt by [Fernandez-Reyes et al, 2019] in Scala, as a library
- Mostly working, no support for parametric types (type system limitation)

Implementing flows

Early attempt: flows from futures

- Attempt by [Fernandez-Reyes et al, 2019] in Scala, as a library
- Mostly working, no support for parametric types (type system limitation)

Our implementation

- Implementation of flows in a fork of the Encore compiler
- Flows added directly in the type system, compiler modified
- Support for parametric types (except in corner cases)!

Encore and flows

- Encore already had control-flow futures and `forward`
- Active object language: future nesting is ubiquitous
- Compiler is simple: $\sim$ 20k Haskell lines

Encore and flows

- Encore already had control-flow futures and `forward`
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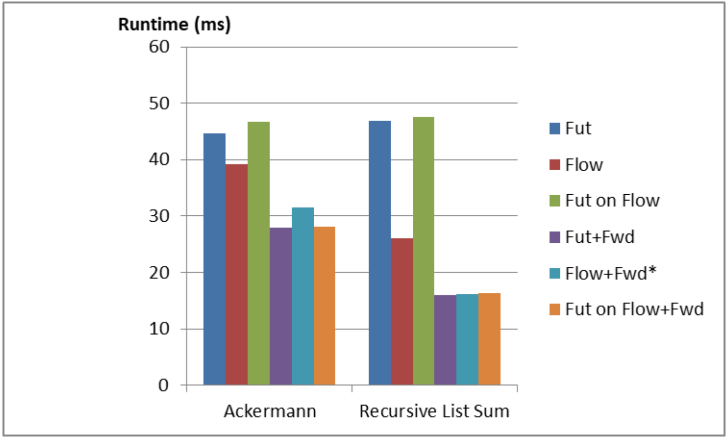
Futures from flows

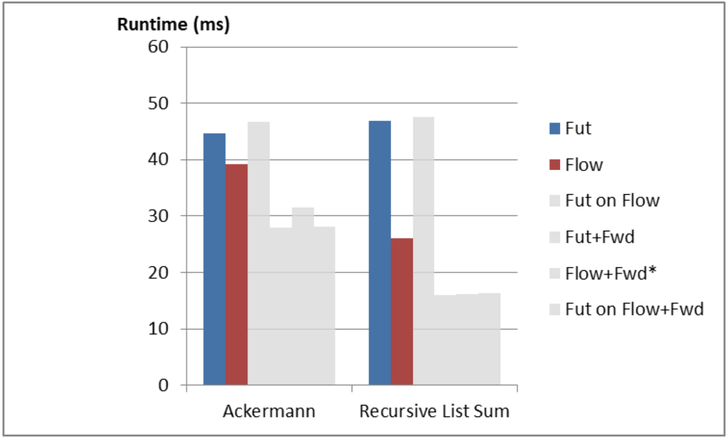
After the implementation of flows:

- Implementation of control-flow futures on top of data-flow ones
- A wrapper class prevents flows from collapsing [Fernandez-Reyes et al 2019]

Benchmarking Flow in Encore



Benchmarking Flow in Encore



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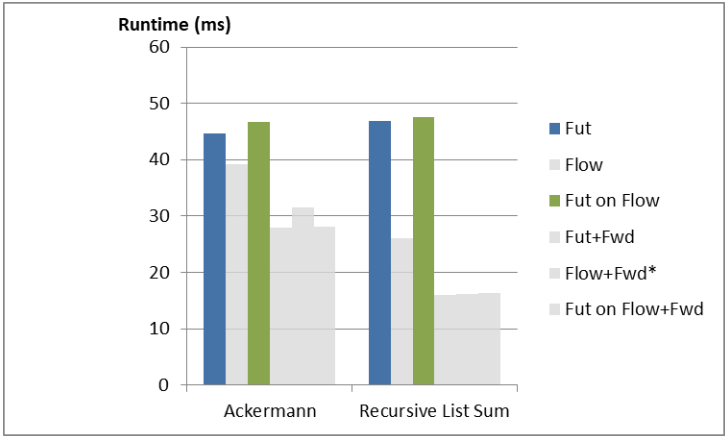

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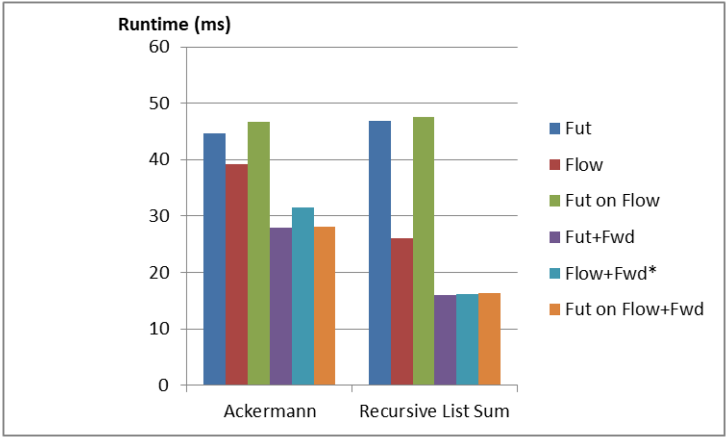

Conclusion

Conclusion on DeF

- We proved that `forward*` and `return` are observably equivalent
  - `return` vs `forward` is just a matter of optimization with flows
- Flows are competitive with regular explicit futures
- A language with native flows can provide regular futures as a library

Today's course summary

- Brief introduction to different ways to implement languages
- Brief introduction to weak memory models
- Advanced futures, typing, semantics and properties