Smoothly Navigating between Functional Reactive Programming and Actors

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Abstract. We formally define an elegant multi-paradigm unification of Functional Reactive Programming, Actor Systems, and Object-Oriented Programming. This enables an intuitive form of declarative programming, harvesting the power of concurrency while maintaining safety.

We use object and reference capabilities to highlight and tame imperative features: reference capabilities track aliasing and mutability, and object capabilities track I/O. Formally, our type system limits the scope, impact and interactions of impure code.

\begin{itemize}
\item Scope: Expressions whose input is pure will behave deterministically.
\item Impact: Data-races and synchronisation issues are avoided. The only way for an actor to behave nondeterministically, is by mutating its state based on message delivery order.
\item Interactions: Signals provide a functional boundary between imperative and functional code, preventing impure code from invalidating functional assumptions.
\end{itemize}

1 Introduction

Parallel programming promises great performance improvements, but it is also a source of undesired nondeterministic behaviour. Actor systems and FRP (Functional Reactive Programming) tame nondeterminism in different ways: each actor sees the world sequentially, and processes a single message at a time. However, messages can be delivered in an unpredictable order. Instead, pure FRP guarantees complete determinism; signals may be processed in various orders and in parallel, but immutability shields us from observing any parallelism.

In 2019, Lohstroh et al. [12] proposed a new actor system that uses reactors. Reactors declare their inputs and outputs, react to messages, and are connected with a composite main function that builds the graph. Effectively, the system uses reactive programming techniques to build actor systems. The ‘reactor network’ can offer stronger guarantees for message delivery/processing order than traditional actor models. However the system does not enforce any properties on behaviour, like determinism or the absence of data races.

In this paper we propose Featherweight Reactive Java (FRJ), a way to blend FRP with actor systems in a minimal subset of Java, inspired by Featherweight
Java (FJ) [9]. FRJ achieves this by using functional reactive programming techniques, which offers all the benefits of the reactor model and control over I/O and state mutation. FRJ fulfils the promise of Lohstroh et al.’s work by allowing the declarative creation of truly deterministic actor systems.

In actor systems, actors have a list of messages that they process one at a time. For simplicity, in our language every object can function as an actor, and thus in memory there is a list of messages near every object record. FRJ’s FRP is inspired by E-FRP’s discrete signals, which are signals that update upon events occurring [4, 20]. FRJ’s signals are a possibly infinite sequence of messages. The messages contain values that have either been computed or are being computed. The head is the most recent message; the tail is an expression that returns a new signal for the next message. Any usages of a signal with a message that has yet to be computed, will wait for the computation to finish. We implement signals via lists of expressions. The computation of each expression is deferred and the result of the computation is a ‘message’. The head and tail of the signal can be accessed using the conventional \texttt{head(\_)} and \texttt{tail(\_)} syntax. Finally, we have a special syntax for lifted method calls: \texttt{a.@m(b,c)}, where \texttt{b} and \texttt{c} are signals. This syntax sends to the actor \texttt{a} a message causing the (asynchronous) computation of \texttt{a.m(head(b),head(c))} and then triggers \texttt{a.@m(tail(b),tail(c))}; until either \texttt{b} or \texttt{c} terminates.

We can connect real world input output with our signals by using object capabilities. We have an expressive type system based on reference capabilities, supporting two fundamental properties: expressions that only use \texttt{imm} references are deterministic, and parallelism can only induce nondeterminism if a mutable actor relies on the delivery order of messages.

2 FRJ

Consider the following class:

```java
1 class Person {
2     method Int age() { return 24; }
3     method Str name() { return "Bob"; }
4     method Str format(Str name, Int age) { return name + ":" + age; }
}
```

Using it, we could write the conventional method call \texttt{p.format(p.name(),p.age())}, to compute a string once. Using FRJ’s lifted method calls, we can write the following in an FRP style:

```java
1 @Int ages = p.@age();
2 p.@format(p.@name(), ages);
```

This creates a signal with messages containing formatted names and ages. If we connected the behaviour of \texttt{age()} to the real world, we would see the formatted names change as Bob grows older. We can also write code in the actor style, by sending individual events to \texttt{p}; \texttt{\@[]} is the empty signal and the syntax \texttt{\@[ ; ]} builds a signal manually.

```java
1 @Int ages = @[p.age();\@[]]
```
This code sends the messages, *age* and *name*, to the actor *p* one time. *p* replies with an *Int* and a *Str* message. When both messages are handled, *p* receives a single message asking to produce the formatted string, parameterised over the name and the age. The creation of messages inside signals is computed in parallel and execution is deferred. Thus, implementing a fork–join is trivial in FRJ:

1. ```
   @Int part1=@x.computePart1();
   Int part2=x.computePart2();
   return head(part1)+part2;
```

The fork-join works because the creation of *part1* does not block because its head is being evaluated in parallel. The `head(part1)` call would block until the expression had been computed and the message was ready.

### 2.1 Grammar

- `cap ::= capability | ∅`
- `CD ::= cap class C implements C {F K M} | interface C extends C {MH_i | ... | MH_n;}`
- `K ::= C(x_1 = ... = x_n; ... this.x_i = x_n;)`
- `F ::= T.f`
- `T ::= mdf C | @T`
- `MH ::= mdf method T m (T_1 x_1 ... T_n x_n);`
- `M ::= MH {return e;}`
- `e ::= x | e.m(τ) | e.f | e.i.f=e2 | new C(τ) | e.@m(τ) | @[e;e'] | @[] | head(e) | tail(e)`
- `v ::= L | [v;S]`
- `E ::= □ | E.m(τ) | v.m(τ E τ) | E.@m(τ) | v.@m(τ E τ) | E.f | E.f=e | v.f=E | new C(τ E τ) | head(E) | tail(E)`
- `mdf ::= imm | mut | capsule | read`
- `Ξ ::= S[e_1;v_2]`
- `μ ::= ρ_1 ... ρ_n`
- `ρ ::= L ↦ C(τ) Ξ`

FRJ is a minimal OO language, where the class table contains classes or interfaces. Classes have methods, *M*, fields, *F*, and a conventional constructor, *K* initialising all of the fields. Interfaces provide conventional nominal subtyping, and for simplicity we do not offer any kind of subclassing. The language makes use of modifiers to implement reference capabilities. The modifiers will be discussed alongside the typing rules because they are transparent to the reduction. FRJ builds over the conventional small step reduction model where a pair `μ|ε` is reduced into a new memory and a new expression. The `E` nonterminal is the evaluation context for the reduction. The memory is a map from object locations *L* to conventional object records. Additionally, every record also maintains a list of pending messages `[Ξ]`. Values are conventional object locations, future signal values *S*, and completed signal values `[v | S]`. Types are class or interface names annotated with a capability modifier *mdf*. The default modifier `imm`
can be omitted for convenience. Types for signals are annotated with $\oplus$. We also support higher-order signals, as $\Phi \Phi T$.

In addition to conventional variables, method calls, field accesses, field updates, and constructor calls, FRJ offers lifted method calls $e \cdot m(T)$, explicit signal construction $\Phi[e; e']$, and the conventional head($e$) and tail($e$) notation. FRJ also offers the empty signal $\Phi[\ ]$, which is a special signal that will not have any more messages in it. The special variable this is implicitly provided as an argument to methods.

2.2 Well-Formedness

Using the auxiliary notation, our well-formedness rules are as follows:

- $\Phi[\ ]$ is not in $\text{dom}(\mu)$ (defined below).
- All classes and interfaces are uniquely named.
- All methods in a given class are uniquely named.
- All fields in a given class are uniquely named.
- All parameters in a given method are uniquely named and are not called this.
- A capsule method parameter can be used zero or one times in the method body.
- All $S$ labelling a $\exists$ inside the memory are unique.
- Fields can only have the type modifiers: \text{imm} or \text{mut}.
- Types containing $\Phi$ must have the \text{imm} modifier.
- Classes can only implement interfaces.
- Interfaces can only extend other interfaces.
- $\mu \mid e$ is well formed if all $L$ in $e$ are in $\text{dom}(\mu)$ (defined below) and all $\text{used}(e) \cup \text{used}(\mu)$ are in $\text{dom}(\mu)$.

$\text{dom}(\mu)$ is the conventionally defined set of all keys ($L$) in the map ($\mu$). $\text{dom}(\mu)$ is the set of all $S$ labelling a $\exists$ inside the memory, and $\text{used}(\mu)$ is defined as follows:

- $\text{used}(\mu) = \text{used}(\mu, \rho_1) \cup \ldots \cup \text{used}(\mu, \rho_n)$,
  - with $\mu = \rho_1 \ldots \rho_n$
- $\text{used}(L \mapsto C(v_1 \ldots v_k) \exists_1 \ldots \exists_n) =$
  - $\text{used}(v_1) \cup \ldots \cup \text{used}(v_k) \cup \text{used}(\exists_1) \cup \ldots \cup \text{used}(\exists_n)$
- $S \in \text{used}(S'(e_1; e_2)) = \text{used}(e_1) \cup \text{used}(e_2)$
- $S \in \text{used}(e)$ if $S$ is a sub-expression of $e$.

2.3 Reduction Rules

The shape of the reduction is: $\mu \mid e \rightarrow \mu' \mid e'$. We use class($C$) to denote the class declaration (CD) for the class $C$ and fields($C$) to denote the list of the fields for the class $C$. Additionally, ‘’ is used as a placeholder in the rules and can match any syntactic term.
\[
L \mapsto C(v_1 \ldots v_n) \quad \text{in } \mu \quad T_1 f_1 \ldots T_n f_n = fields(C) \quad \text{(fAccess)}
\]

\[
\mu, L.f_i \rightarrow v_i \quad \text{in } \mu
\]

\[
T_0 f_0 \ldots T_n f_n = fields(C) \quad \rho_0 = L \mapsto C(v_1 \ldots v_n) \quad \rho_1 = L \mapsto C(v_1 \ldots v_n) \quad \text{(fUpdate)}
\]

\[
\mu, \rho_0 \mid L.f_0 = v \rightarrow \mu, \rho_1 \mid v
\]

\[
\mu \mid \text{new } C(v_1 \ldots v_n) \rightarrow \mu, L \mapsto C(v_1 \ldots v_n) \mid L \quad \text{(new)}
\]

\[
L \mapsto C(v) \quad \text{in } \mu \quad \text{method } m \ (\langle \_ x_1 \ldots x_n \rangle \ \text{return } e; \} \) \text{ in class}(C) \quad \text{(mCall)}
\]

\[
\mu, \rho \mid L.m(v_1 \ldots v_n) \rightarrow \mu \mid e[\text{this} = L, x_1 = v_1 \ldots x_n = v_n]
\]

\[
\mu \mid e \rightarrow \mu \mid e' \quad \text{(EHead)}
\]

\[
\mu, \rho \mid S[e; e_0] \mid e_1 \rightarrow \mu, \rho \mid S[e'; e_0] \mid e_1
\]

\[
\mu \mid e \rightarrow \mu \mid e' \quad \text{(ETail)}
\]

Field updates, field access, object construction and method call are standard. Contextual rules \((E, E\text{Head}, \text{and } E\text{Tail})\) guide the parallel reduction: \((E)\) allows us to reduce the main expression, while \((E\text{Head})\) reduces the last message of an object. When the value is produced, rule \((E\text{Tail})\) executes the expression creating the next stream node. Note that since the memory \(\mu\) is a set, the rules can work on any \(\rho\) in \(\mu\). The \(\rho\) non-terminal has a list of \(\rightarrow\) at its end; thus by writing \(\mu, \rho \mid S[e; e']\) we are selecting the last message of an arbitrary object in memory.

\[
\mu \mid \text{head}([v; S]) \rightarrow \mu \mid v \quad \text{(head)}
\]

\[
\mu \mid \text{tail}([v; S]) \rightarrow \mu \mid S \quad \text{(tail)}
\]

\[
\mu \mid \text{tail}(@[] \rightarrow \mu \mid @[] \quad \text{(tailEmpty)}
\]

\[
\mu, \rho \mid S[v; S'] \mid e_1 \rightarrow (\mu, \rho \mid e_1)[S = [v; S']] \quad \text{(msgComplete)}
\]

Field updates, field access, object construction and method call are standard. Contextual rules \((E, E\text{Head}, \text{and } E\text{Tail})\) guide the parallel reduction: \((E)\) allows us to reduce the main expression, while \((E\text{Head})\) reduces the last message of an object. When the value is produced, rule \((E\text{Tail})\) executes the expression creating the next stream node. Note that since the memory \(\mu\) is a set, the rules can work on any \(\rho\) in \(\mu\). The \(\rho\) non-terminal has a list of \(\rightarrow\) at its end; thus by writing \(\mu, \rho \mid S[e; e']\) we are selecting the last message of an arbitrary object in memory.

\[
\mu, \rho \mid S[e; e_0] \mid e_1 \rightarrow (\mu, \rho \mid e_1)[S = @[]] \quad \text{(Empty)}
\]
The rule (head) is conventional and simply reduces to the current value of a completed signal. When the expression is well typed, the tail of a message is expected to be a signal that will eventually contain the next value, rule (tail) can be used to get that continuation signal.

When a message has been completely computed, rule (msgComplete) removes the message from the memory, and replaces all of the references to $S$ with $e_1: e_2$.

Therefore, the rule (msgComplete) enables a form of synchronisation between the messages and their consumers.

When the message execution tries to access the head of the empty signal, rule (Empty) terminates the signal, removing the message $S$ and by replacing all occurrences of $S$ with $\emptyset[l]$. 

This group of two rules (explicitS, and liftS) deals with the creation of signals.

For the creation of signals, the rule (explicitS) reduces signal constructors into a message ($\emptyset[l]$) and places it on a new empty actor. The signal constructor expression is then replaced with the fresh signal ($S$) that was just associated with the message.

The alternative way to create signals in FRJ is through lifting methods. liftS reduces lifted method calls by creating a $\emptyset[l]$ that gets placed onto the receiver containing a head of the traditional method call with arguments of the head of all of its inputs. The tail of this new $\emptyset[l]$ will be the same lifted method call, but with the tail of all of the inputs as the inputs for the new lifted call. Effectively, the method now reacts to its inputs.

Finally, the rule (garbage) gets rid of the part of memory that is unreachable starting from the main expression. Note that we cannot arbitrarily split the memory. We can only split it in such a way that the resulting $\mu | e$ is well formed. An important consequence of our garbage collection rule is that messages can be collected too, even during their computation. However, due to our well-formedness rules, messages can only be collected if the receiver actor object is collected, and an object can only be collected if there are no other references to its address and to any of the $S$ in its mailbox.
2.4 Reference capabilities

Parallel computation is inherently part of FRP and actor systems. FRJ uses reference capabilities to tame the nondeterminism that would otherwise arise from aliasing and mutability. FRJ supports the three traditional reference capabilities: \texttt{imm}, deeply immutable (the default); \texttt{mut} mutable and \texttt{read}, the common supertype of both \texttt{imm} and \texttt{mut}. In addition, FRJ supports \texttt{capsule}; a reference that dominates its ROG \texttt{mut} (reachable object graph) [7]. In OO languages, ROG(L) = \overline{L} is all the locations transitively reachable from the fields of \(L\). With reference capabilities, mutable ROG \texttt{mut} (L) = \overline{L} is all the locations transitively reachable from \(L\) only following mutable fields.

Assuming a traditional \texttt{Person} class, the following is an example of reference capabilities:

```java
1 mut Person mP=new Person("Bob",24);
2 imm Person iP=new Person("Bob",24);
3 read Person rP=mP;
4 mP.setAge(25);//ok, now rP.getAge()==25
5 iP.setAge(25);//type error
6 rP.setAge(25);//type error
7 rP=iP;//ok, read is supertype of imm/mut
```

Note how the same object may be pointed at the same time by multiple references with different modifiers. Capsule references can be obtained when the aliasing is under control, and can be used to create immutable references. Capsule references can be used to create immutable references from non-immutable objects. Capsule references can only exist in expressions, and the whole mutable object graph reachable from a capsule reference can only be reached from that specific capsule reference. In this way, the capsule reference is the sole access point to a group of mutable objects. Reference capabilities have the following subtype relation:

- capsule \leq mdf
- mdf \leq read

Thus, all of the reference capabilities are subtypes of \texttt{capsule} and supertypes of \texttt{read}, \texttt{mut} and \texttt{imm} are not comparable to each other.

The main advantage of reference capability over older forms of aliasing control [1,8], is that references can be promoted/recovered to a subtype when the right conditions arise. In this work we rely only on \textit{multiple method types}:

If \texttt{mdf method T m (T_1 x_1 ... T_n x_n) \in class(C)}, \(T_0 = mdf' C\) and \(mdf' \leq mdf\) then

\[
\text{methTypes}(T_0, m) = \{ T_0 ... T_n \rightarrow T, \quad (T_0 ... T_n \rightarrow T)[mut = \text{capsule}], \quad (T_0 ... T_n \rightarrow T)[mut = \text{capsule}, read = \text{imm}] \}
\]

Where notation \([mut = \text{capsule}]\), replaces all of the \texttt{mut} with \texttt{capsule}. For example, the following code is correct:

```java
1 class Box { mut F f; Box(mut F f) { this.f=f; }
2    read method read F f() { return this.f; } }
```
class MakeBox{
method mut Box of(mut F f){ return new Box(f); }
}
capsule F f=..//we have a capsule f
capsule Box b=new MakeBox().of(f);
imm Box immB=b; imm F immF=immB.f();

On line 4, method of(f) was declared taking an imm receiver and a mut parameter, and returning a mut, but when called with a capsule parameter (line 6), we can promote the result to capsule. On line 2, method f() was declared taking a read receiver and returning a read, but when called with an imm receiver (line 7) we can promote the result to imm.

2.5 Object capabilities

An object capability is an object whose methods can do privileged operations. While reference capabilities keep mutability and aliasing under control, we rely on object capability [14] to tame I/O. Our reduction rules do not model I/O directly, but we assume predefined capability classes containing mut methods doing all of the desired I/O interactions. Since only mut methods of capability classes can do nondeterministic I/O, we keep I/O under control by allowing only the main and mut methods of capability classes to create instances of capability classes [6]. In this way, any method that only takes immutable objects as input is guaranteed to be deterministic.

In FRJ, the default reference capability is carefully designed to require explicit syntax to introduce any impurity and non-determinism. Because imm is the default reference capability, imperative features are controlled by default. The values of signals are always imm, so every other reference being imm by default makes using signals easier. Additionally, outside of the main expression, all classes may not perform any I/O or other side effects without being declared as a capability or taking an object capability as input.

2.6 Typing Rules

FRJ’s typing environment has three components: \( \Gamma \), the mapping between variables and types; \( \Sigma \), the mapping between a memory address and object locations; and \( cap \), a flag identifying if the expression is allowed to instantiate capability classes.

We will use notation \( capOf(C) \) and \( capOf(T) \) to denote the capability modifier of a given class.

\[
\begin{align*}
&\frac{}{\quad \text{cap} ; \Sigma ; \Gamma \vdash x : \Gamma(x)}^{(x)} \\
&\frac{\text{cap} ; \Sigma ; \Gamma \vdash e : T'}{\text{cap} ; \Sigma ; \Gamma \vdash e : T}^{(\text{sub})}
\end{align*}
\]

\[
\frac{\text{cap} ; \Sigma ; \Gamma \vdash L : mdf \Sigma(L)}{\quad \text{cap} ; \Sigma ; \Gamma \vdash L}^{(L)}
\]
Variable typing and subsumption are standard.

The rule (L) types memory references as the class of the object it points to and the modifier of the reference:\(^1\).

\[
\begin{align*}
\text{cap; } \Sigma; \Gamma \vdash e : \text{mdf } C & \quad \text{cap; } \Sigma; \Gamma \vdash T_1 f_1 \ldots T_n f_n = \text{fields}(C) \\
\text{cap; } \Sigma; \Gamma \vdash e.f_i : T_i + \text{mdf}
\end{align*}
\]  
(IAccess)

\[
\begin{align*}
\text{cap; } \Sigma; \Gamma \vdash e_1 : \text{mut } C & \quad \text{cap; } \Sigma; \Gamma \vdash T_1 f_1 \ldots T_n f_n = \text{fields}(C) \\
\text{cap; } \Sigma; \Gamma \vdash e_2 : T_i & \quad \text{cap; } \Sigma; \Gamma \vdash e_1.f_i = e_2 : T_i
\end{align*}
\]  
(IUpdate)

Field access and field update are conventional with the exception of modifiers being applied to the result of a field access and the added requirement that the receiver of a field update must be \text{mut}. The rules for the composition for the reference capabilities of the result of a field access are:

- \(\text{\text{- } \text{msdf } C + \text{imm } = \text{\text{- } \text{msdf } C + \text{imm } C}\)
- \(\text{\text{- } \text{msdf } C + \text{mut } = \text{\text{- } \text{msdf } C + \text{msdf } C}\)
- \(\text{\text{- } \text{msdf } C + \text{capsule } = \text{\text{- } \text{msdf } C}\)
- \(\text{\text{- } \text{mut } C + \text{read } = \text{\text{- } \text{read } C}\)
- \(\text{\text{- } \text{imm } C + \text{read } = \text{\text{- } \text{imm } C}\)

For example, with a field access, if the receiver had the \text{read} modifier and the field had the \text{imm} modifier, result would be \text{imm}. Alternatively, if the receiver was \text{read} and the field was \text{mut}, the result would be \text{read}.

\[
\begin{align*}
T_1 f_1 \ldots T_n f_n = \text{fields}(C) & \quad \text{cap; } \Sigma; \Gamma \vdash e_i : T_i[n] \quad \text{either } \text{capOf}(C) = \emptyset \text{ or } \text{cap} = \text{capability} \\
\text{cap; } \Sigma; \Gamma & \vdash \text{new } C(e_1 \ldots e_n) : \text{mut } C
\end{align*}
\]  
(new)

Object instantiation is also mostly conventional. The major difference is that if the class is marked as \text{capability}, then the object can only be created in the main method or in a \text{mut} method of another capability class; see rule (method) on page 11.

\[
\begin{align*}
T_1 f_1 \ldots T_n f_n = \text{fields}(C) & \quad \text{cap; } \Sigma; \Gamma \vdash e_i : T_i[n] \text{mdf } = \text{imm} \\
\text{cap; } \Sigma; \Gamma & \vdash \text{new } C(e_1 \ldots e_n) : \text{imm } C
\end{align*}
\]  
(newImm)

If the constructor arguments are all \text{imm}, then the object created can be typed with the \text{imm} modifier; also capability classes can be instantiated by this rule, since only the \text{mut} methods can do privileged operations.

\[
\begin{align*}
T_0 \ldots T_n & \mapsto T \text{ in methTypes}(T_0, m) & \quad \text{cap; } \Sigma; \Gamma \vdash e_i : T_i \\
\text{cap; } \Sigma; \Gamma & \vdash e_0.m(e_1 \ldots e_n) : T
\end{align*}
\]  
(mCall)

\(^1\) To complete a proof of soundness, we would likely need to instrument the reduction to keep track of the pair \text{L:mdf}. 

\[
\begin{align*}
T_1 f_1 \ldots T_n f_n = \text{fields}(C) & \quad \text{cap; } \Sigma; \Gamma \vdash e_i : T_i[n] \text{mdf } = \text{imm} \\
\text{cap; } \Sigma; \Gamma & \vdash \text{new } C(e_1 \ldots e_n) : \text{imm } C
\end{align*}
\]  
(newImm)

If the constructor arguments are all \text{imm}, then the object created can be typed with the \text{imm} modifier; also capability classes can be instantiated by this rule, since only the \text{mut} methods can do privileged operations.
Our method call type rule is mostly conventional but relies on `methTypes`, and thus is more flexible than the conventional one.

\[
\text{cap;} \Sigma; \Gamma \vdash e_0 : T_0 \quad T_0 \ldots T_n \mapsto T \text{ in } \text{methTypes}(T_0, m)
\]

\[
\text{cap;} \Sigma; \Gamma \vdash e_i : @T_i \quad \forall i \in 1..n \quad \text{validActor}(T_i)
\]

\[
\text{cap;} \Sigma; \Gamma \vdash e_0 . @m(e_1 \ldots e_n) : @T
\]

(mCall@)

The major difference between rule (mCall) and rule (mCall@) is that all of the argument types are lifted (@T) and the receiver must be a `validActor(T_0)`: either the receiver is immutable (T_0 = imm ⊥) or the receiver is a capability instance and have only imm fields (capOf(T_0) = capability and mut C f \notin fields(T_0)).

Actors may receive messages in any order; while immutable actors cannot be influenced by such order, a mutable actor may use the messages to update the value of a field\(^2\).

`validActor(T_0)` prevents this issue, but it requires mutable actors to be instances of capability classes. Note that there is no need for all of the actors to be created in `main`; it is sufficient to create a single capability ActorSystem object that creates new actors using some mut method.

\[
\text{cap;} \Sigma; [\text{only } \text{imm, capsule}] \vdash e_1 : T
\]

\[
\text{cap;} \Sigma; [\text{only } \text{imm, capsule}] \vdash e_2 : @T
\]

(fullSignal)

The rule (fullSignal) is for a signal constructor with both a head and a tail. The rule enforces that only imm and capsule variables can be captured by the deferred executed expressions inside the signal.

\[
\text{cap;} \Sigma; [\text{only } \text{imm, capsule}] \vdash [\vdash] : @T
\]

(emptySignal)

The rule (emptySignal) is similar to the conventional rule for typing empty lists, as the empty signal can assume any signal type; not unlike how [] in Haskell is generic and valid for any list type.

\[
\text{cap;} \Sigma; \Gamma \vdash e : @T
\]

(head)

\[
\text{cap;} \Sigma; \Gamma \vdash \text{head}(e) : T
\]

(tail)

\[
\text{cap;} \Sigma; \Gamma \vdash e : @T
\]

Rule (head) extracts the type of the value in the head and rule (tail) preserves the type of the expression.

\[
\text{cap;} C \vdash M_i \quad \text{overrideOk}(C', M_i) \quad \forall C' \in \overline{C} \quad \text{dom}(C') \subseteq \text{dom}(C) \quad \forall C' \in \overline{C} \quad \text{OK}
\]

\[
\text{cap} \quad \text{class} C \text{ implements } \overline{C} \{ F \ K M_1 \ldots M_n \} \quad \text{OK}
\]

(class)

\(^2\) If such an actor could be freely created, then we could use it to forge a no-args method with a nondeterministic result.
The last three type rules (class, interface, and method) are standard with the exception of rule (method), where every \texttt{mut} method in a \texttt{capability} class is typed as a capability method. We omit the trivial but tedious definition for \texttt{overrideOk}(C', MH_i), checking if a method signature can override a potential method with the same name defined in the super interface: if another method with the same name exists, the two method types must be identical.

3 Example

The scenario used in the proposal of the first-order purely FRP language, \texttt{Emfrp} [21], is an air conditioning unit’s controller. The inputs are temperature, humidity, and the current power state of the unit. The output is what the power state of the unit should be. To show how FRJ works, the same scenario can be done with our system. For this example we are taking the liberty of using number/boolean literals and postfix operators for simplicity’s sake.

We assume the existence of two capability classes: \texttt{Sensors}, which contains methods to read the physical sensors on the AC unit and a clock; and \texttt{AC}, which interacts directly with the hardware to change power states.

A \textit{discomfort index} is calculated based on the temperature and the humidity to determine how uncomfortable the room is. We represent that with this actor:

```cpp
1 class ComfortComputer {
2     method Float discomfort(Float temp, Float hum) {
3         return 0.81 * temp + 0.01 * hum * (0.99 * temp - 14.3) + 46.3;
4     }
}
```

The actor \texttt{ACController} computes if the unit should be on or off, depending on the discomfort index and its current power state. The current power state of the unit is needed to apply hysteresis, so that the unit does not constantly change power state. The first implementation is in the traditional actor style with mutable state:

```cpp
1 capability class ACController{
2     Bool isOn;//can be updated
3     ACController(Bool isOn) {this.isOn=isOn;}
4     read method Float hysteresis() {
5         return this.isOn?-0.5:0.5;
6     }
7     mut method Bool powerSwitch(Float d) {
8         this.isOn=d>(75.0+this.discomfort()); return this.isOn;
9     }
```
Note how `ACController` is a valid mutable actor: It is a capability class where the only field is of type `imm Bool`. Note how the field can still be updated (line 7); FRJ only requires the referred object (the `Bool`) to be deeply immutable.

We now have an actor that will generate current discomfort values and another actor that will determine the current power state. In `main`, we can connect them to the sensors to make our program react to the real world:

```java
// Get sensor input
mut Sensors s=new Sensors(); //capability
@Bool tick=s.clock(); // emits every second
@Float temps=s.temp(tick); @Float humidities=s.humidity(tick);
// Decide power state
@Float discomfort=new ComfortComputer().discomfort(temps,humidities);
@Bool powerState=new ACController(false).powerSwitch(discomfort);
// Apply power state
mut AC ac=new AC(); //capability
ac.setPower(powerState);
```

One nice feature of our system is that, because inputs are waited for, the `tick` input coordinates the system to update once a second at maximum. The `tick` dependency is similar to using Rx’s `Interval` operator as a source [17]. That feature is important: it avoids mailbox overflow when one sensor is faster than the other.

We now reimplement `ACController` in a more traditional FRP approach, where state is kept via recursion with signals, much like Elm’s `foldp` pattern (before Elm removed FRP from their language⁴) `foldp` is short for “fold over the past” [⁵] and is typed `(a -> b -> b) -> b -> @a -> @b`. We can define `FoldP` in FRJ, extended with some modern Java features:

```java
interface FoldP<I,O>{
    method O apply(I v,O old);
}
static method <I,O> @O of(FoldP<I,O> f,O initial,@I signal){
    O out=f.apply(head(signal),initial);
    return @[out;FoldP.of(f,out,tail(signal))]; }
class ACController{//functional using FoldP
    method Float hysteresis(Bool isOn){return isOn?-0.5:0.5;}
    method @Bool powerSwitch(@Float discomfort){
        return FoldP.of(
            (d,isOn)->d>(75.0+this.hysteresis(isOn)),
            false,discomfort);}
}
```

To switch to the FRP style while keeping the same behaviour, on line 7 of the previous main we can use `new ACController().powerSwitch(discomfort)`.

Both programming styles are highly parallelisable, with clear dependency chains, and a fairly compact code footprint. FRJ allows for smooth transitions between the FRP and Actor model approaches to concurrent programming.

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⁴ https://elm-lang.org/news/farewell-to-frp
4 Related Work

The potential for connection between reactive programming and the actor model has been a subject of active research over the past 4 years. The reactor model’s attempt to create deterministic actors using reactive programming [12] offers guarantees on deterministic message delivery and processing order to ensure that all nodes requesting an input get it and process it before the next message is sent. However, by abstracting message passing with FRP’s signal primitive, FRJ enables immutable and pure actors that do not need to be bound by the reactor model’s strict ordering rules.

Work has been done by Van den Vonder et al. [19] on the ‘actor-reactor model’ (ARM), which instead of replacing actors with reactors, creates a joint model, where actors can be nondeterministic. The reactors in the ARM should not be confused with the Lohstroh et al.’s reactors; ARM’s reactors are always pure and deterministic. The ARM approach is novel and sensible, but FRJ takes a different path. FRJ does not have the distinction between ‘actors’ and ‘reactors’. Instead, we attempted to unify the two systems. FRJ’s unified approach does still make a distinction between deterministic and nondeterministic actors using object capabilities, but a pure FRJ actor is able to perform more complex tasks than an ARM reactor. Ultimately, the ARM is very compelling, but we think that a unified approach results in simpler systems.

XFRP [18] offers an interesting model for executing pure FRP on an actor-based runtime. Using XFRP would be a similar experience to using FRJ without any object or reference capabilities. The language has fewer sources of nondeterminism to control because it delegates side effects to components that are external to the program. Shibani et al. note their main source of nondeterminism as the @last operator, which is essentially syntactic sugar for foldp. Glitch is a common issue with systems inspired by FRP. Single source glitch freedom means that all nodes (lifted functions for FRJ) that have one signal as an input, will get updates at the same time [15]. If a system does not have glitch freedom, then parts of the application that depend on the same signals could be in an inconsistent state until they get the latest message. If multiple stateful inputs are given to a signal function, glitch freedom can be violated in XFRP. XFRP manages to get around the issue by adding an option to change the semantics of their language to the same as FRJ’s lifted method call, with a feature they call source unification. FRJ effectively treats all arguments to a lifted function as a single input. FRJ’s behaviour has some interesting implications for glitch freedom. Because FRJ’s evaluation model provides for single source glitch freedom in the same way as XFRP [18], and all arguments to a lifted function can be considered a single source; FRJ has complete glitch freedom [13].

As a possible implementation technique, FRJ actors can be implemented with a variety of actor frameworks, including Akka [11]. Alternatively, there is no reason why a simpler technique, like Emfrp’s actor implementation [21] could not be used. Similarly to Pony [3], our actor system uses shared-memory message passing guarded by reference and object capabilities.
5 Conclusions and Future Work

In this foundational work, we defined FRJ, a core OO calculus modelling both FRP and actor systems. FRJ supports traditional imperative field updates and I/O, but it keeps control of side effects using reference and object capabilities. The work on FRJ is far from complete, we plan to formally model generics and lambdas, and to study possible efficient implementation strategies. Garbage collection may require particular attention since it can stop running computations. We plan to relax the restriction on the state of mutable actors, and to develop some case study, to explore useful programming patterns mixing Actors and FRP, and potentially to look into applying more performant and newer forms of FRP such as Yampa’s version of arrowized FRP [2,16]. FRJ can model most Actor, FRP, and RP patterns. For example, a signal supplier can model hot or cold signals [10] by either returning a reference to an existing signal or by returning a newly created one. FRJ’s signals can be finite or infinite, and they can either be connected with real world devices or just manipulate objects in memory. FRJ streams can be dynamically created and wired while preserving equational reasoning for all expressions that only take in immutable values as input. Although a proof is still future work, we believe FRJ preserves two formal properties:

- If the reduction of an expression $e$ is nondeterministic, then $e$ refers to a pre-existing mutable value.
- There are no data races, that is: for all well-typed expressions, two different nondeterministic reduction steps will not execute a field update on the same receiver object.

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