Camila Revival: VDM meets Haskell

Overture Workshop

18 July 2005, Newcastle upon Tyne, UK

Co-located with FM'05

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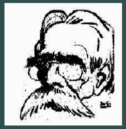
CAMILA Revival

FM tools at Minho



- **CAMILA** software (1986-1997)
- **VDMTools** (1998-2005)

What next?

- CAMILA Revival (**Haskell** based)
- Overture (**Eclipse** based)

Why **Haskell**?

CAMILA Revival

Objectives

- FM perspective: exploit **Haskell**'s advanced type system and extensive suite of libraries for specification purposes.
- FP perspective: bring **VDM** features, such as constrained datatypes and partial functions, into the functional programmer's reach.

So far

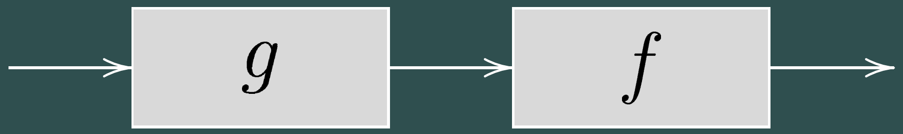
- Capture **VDM** operations in **Haskell** libraries (**CPrelude**)
- Implement **VDM** interpreter in **Haskell** (**iCamila**)
- Model **VDM** state features monadically
- Model **VDM** partiality features monadically (current paper)

VDM versus Haskell

Specification	Programming
Set-theoretic	Type-theoretic
Numerous built-in operators	Numerous library functions
Strict	Lazy
Implicit functions	?
Datatype invariants	?
Pre / post conditions	?
State	?

Why Haskell?

Component-oriented design relies on compositionality — the true basis of software construction — for instance



Recall

- Unix pipes `g | f`
- Functional composition, $\lambda x.f(g(x))$
- etc

Why Haskell?

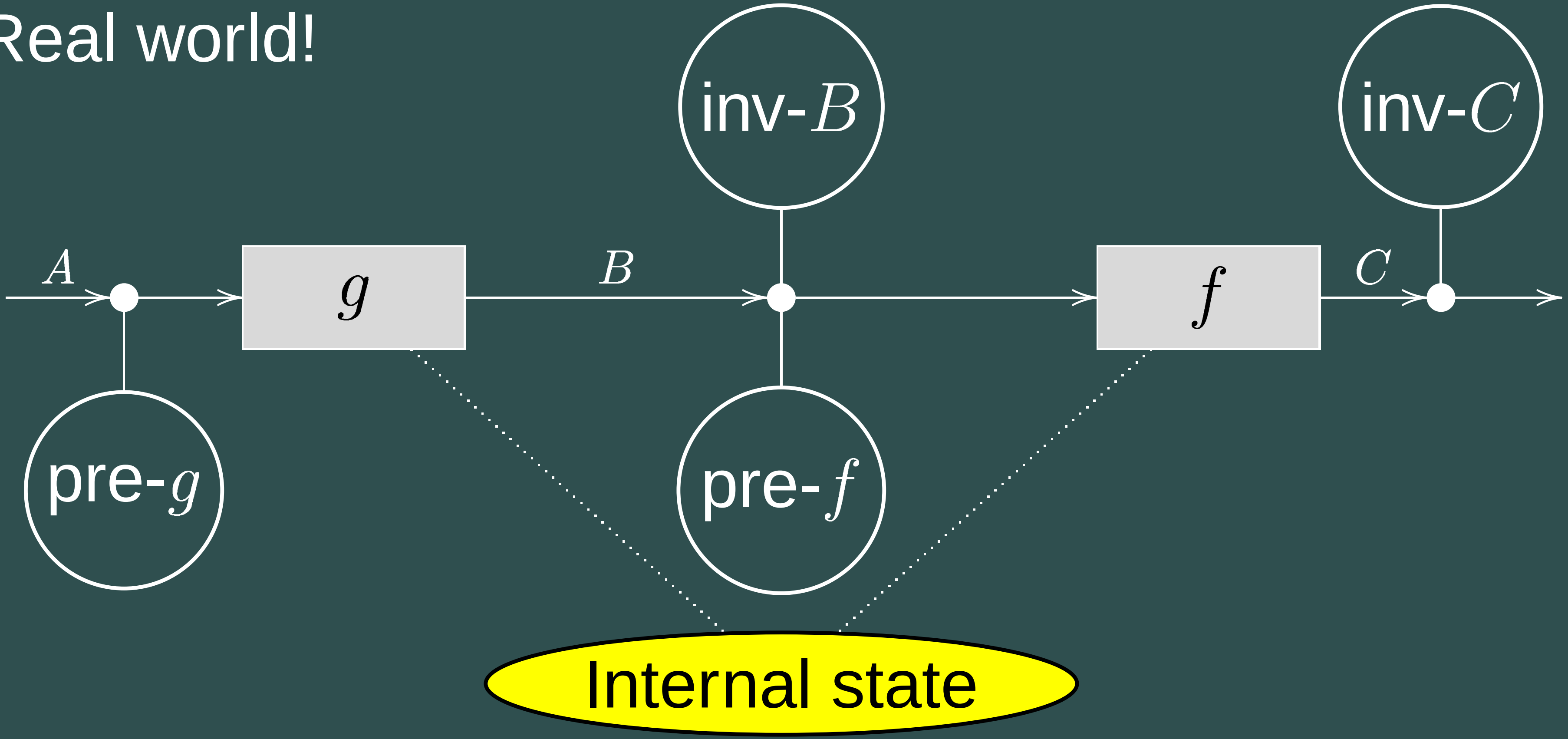
Ideal world:

$$[\![\;\longrightarrow \boxed{\;g\;} \longrightarrow \boxed{\;f\;} \longrightarrow\;]\!] = [\![f]\!] \cdot [\![g]\!]$$

Why Haskell?

Ideal world:

Real world!

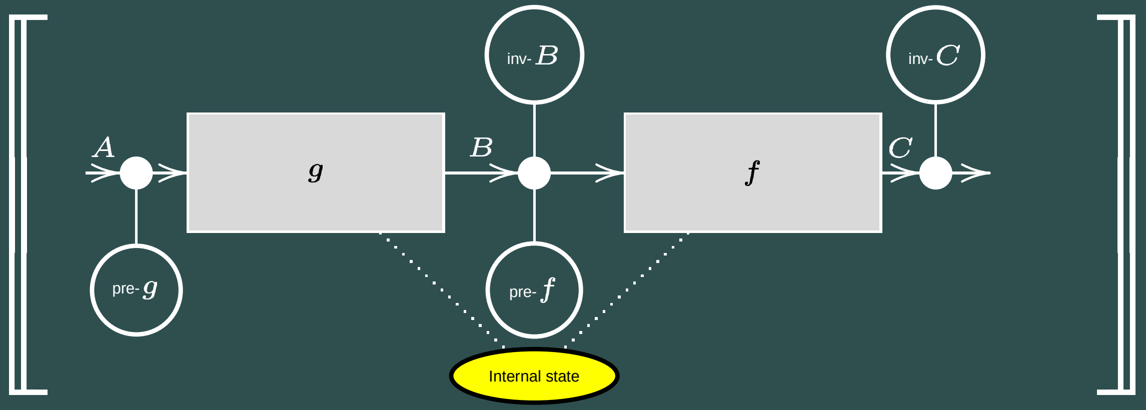


Why Haskell?

Ideal world:

$$= [\![f]\!] \cdot [\![g]\!]$$

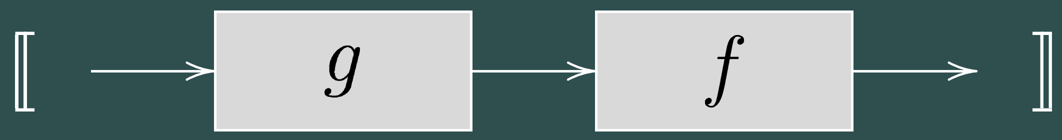
Semantics of real world ?



$$= [\![f]\!] \; \textcircled{?} \; [\![g]\!]$$

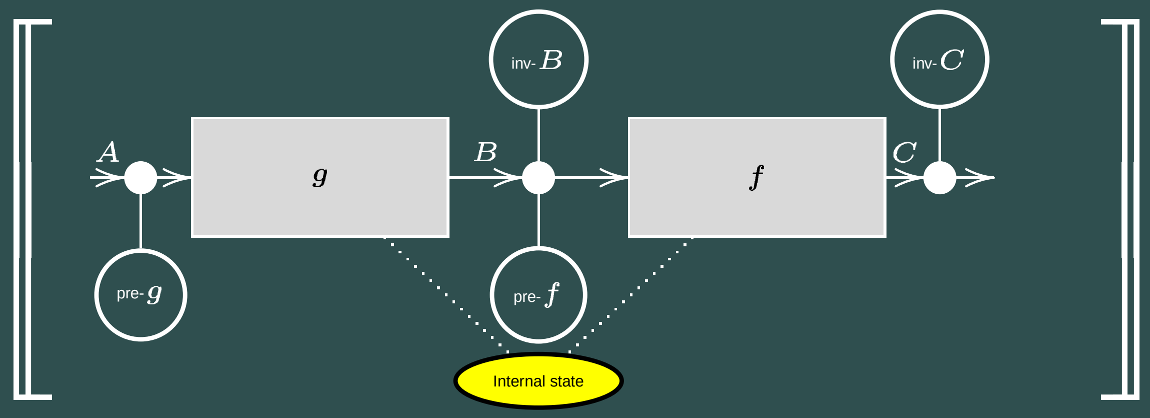
Why Haskell?

Ideal world:



$= [\![f]\!] \cdot [\![g]\!]$

Semantics of real world ?



$= [\![f]\!] \textcircled{?} [\![g]\!]$

Claim: just write (monadic) $[\![f]\!]$. ! $[\![g]\!]$ instead of $[\![f]\!] \cdot [\![g]\!]$

Why monads

Compare:

$$(f \cdot g)a \quad = \quad \texttt{let b = g(a) in f(b)}$$

with

$$(f \;\texttt{.!}\; g)a \quad = \quad \texttt{do \{ b <- g(a); f(b) \}}$$

Why monads

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where types are, in the second case, as follows

$$\begin{tikzcd}
A \arrow[r, "g"'] & \mathsf{M}\ B & \\
 & B \arrow[u, dotted, dash] \arrow[r, "f"'] & \mathsf{M}\ C
\end{tikzcd}$$

Why monads

Compare:

$(f \cdot g)a$ = `let b = g(a) in f(b)`

with

$(f\ \texttt{.!}\ g)a$ = `do { b <- g(a); f(b) }`

In detail:

$$\begin{tikzcd}
A \arrow[r, "g"'] \arrow[rrr, bend left, "f\ \texttt{.!}\ g"] & \mathsf{M}\ B \arrow[r, "\mathsf{M}\ f"'] \arrow[d, dash, dotted] & \mathsf{M}(\mathsf{M}\ C) \arrow[r, "\mu"'] \arrow[d, dash, dotted] & \mathsf{M}\ C \\
 & B \arrow[r, "f"'] & \mathsf{M}\ C &
\end{tikzcd}$$

Why monads

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$$(f \cdot g)a \quad = \quad \texttt{let b = g(a) in f(b)}$$

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Example (list monad):

$$\begin{tikzcd}
A \arrow[r, "g"'] \arrow[rrr, bend left, two heads, "f \,\mathtt{.!} g"] & {[B]} \arrow[r, "map\ f"'] \arrow[d, dash, dotted] & {[[C]]} \arrow[r, two heads, "concat"'] \arrow[d, dash, dotted] & {[C]} \\
 & B \arrow[r, "f"'] & {[C]} &
\end{tikzcd}$$

Standard definition

$$(f \;\texttt{.!}\; g)a \;=\; \texttt{g(a) »= f}$$

where

```
class Monad m where
   return ::  a -> m a
   (>>=) ::  m a -> (a -> m b) -> m b
   (>>) ::  m a -> m b -> m b
   fail ::  String -> m a
```

Partiality and the `Error` monad

Which monad M? A popular choice for handling partiality is

- datatype

```
data Error a = Err String | Ok a
```

- that is, monad

```
instance Monad Error where
    return b = Ok b
    (Err e) >>= f  =  Err e
    (Ok a)  >>= f  =  f a
```

First experiment

“Monadify” normal functions,

$$[\![\mathrm{f}]\!]\texttt{a} = \texttt{Ok (f a)}$$

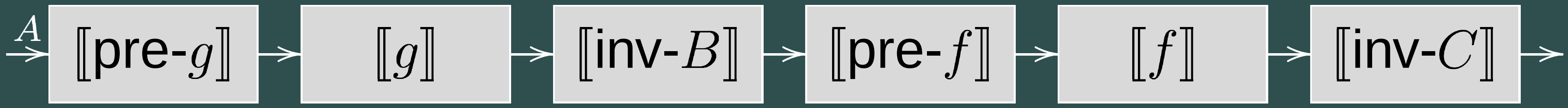
and convert conditions and invariants to monadic partial identities, eg.

$$\begin{aligned} [\![\texttt{inv}]\!]\,\texttt{a} = {} & \texttt{if (inv a)} \\ & \texttt{then (Ok a)} \\ & \texttt{else Err "Invariant violation"} \end{aligned}$$

(So $[\![\texttt{inv}]\!]$ `:: a -> Error a` while `inv :: a -> Bool`)

Back to the real world

In this way, we get a very simple, “pipelined” approach to composition



$$\xrightarrow{A} [\![\text{pre-}g]\!] \to [\![g]\!] \to [\![\text{inv-}B]\!] \to [\![\text{pre-}f]\!] \to [\![f]\!] \to [\![\text{inv-}C]\!] \to$$

where the arrows are `Error`-monadic —think of $($ `.!` $)$ instead of $(\cdot)$ —that is

```
do { pre-g a;
     b <- g a;
     inv-B b; pre-f b;
     c <- f b;
     inv-C c
}
```

Monadic invariant example

Invariant associated to a relational table `t` with schema `s` in a RDB system:

```
inv (Rel s t) = do {
     m <- mfoldS munion’ (Ok emptyPf) (nmap (id *-> valType) t)
          ‘otherwise_‘ "Tuple schemas are not mutually compatible" ;
     check (relSchemaOk m) (Rel s t)
          "At least one tuple type does not match relation schema" ;
     check fdpOk (Rel s t)
          "The key-property is not valid in the relation"
     }
       where
         relSchemaOk m r = m <= (id *-> (valType . defaultV)) (schema r)
         fdpOk (Rel s t) = fdp(nmap (tnest (getKeyAtts s)) t)
```

(Excerpt of Necco’s Haskell model of a relation in a RDB system.

Note the successively contextualized error messages interspersed

with the monadic code.)

Why this not enough

- We are stuck to a single monad (`Error`) and a single **evaluation mode** (fail)

We would like to be able to switch among

- **free fall** —no checking performed whatsoever.
- **warn** —when invariants and conditions are found violated, a warning will be issued, but computation proceeds as if nothing happened.
- **fail** —invariant and conditions checked, and when found violated a run-time error is forced immediately.
- **error** —invariants and conditions are checked, and when found violated an error or exception will be thrown.

Running example (VDM)

VDM model of stacks of odd integers —(partial) datatype

```
Stack = seq of int
        inv s = forall a in set elems s & odd(a);
```

and (partial) functions

```
empty : Stack -> bool
empty(s) == s = [];

pop : Stack -> Stack
pop(s) == tl s
pre not empty(s);
```

```
top : Stack -> int
top(s) == hd s
pre not empty(s);

push : int * Stack -> Stack
push(p,s) == [p] ^ s
pre odd(p) ;
```

Constrained datatypes (Haskell)

We go back to invariants as Boolean functions and define class

```
class CData a where
   inv :: a -> Bool
   inv a = True -- default
```

so that **invariants** propagate dynamically, eg. listwise

```
instance CData a => CData [a] where
    inv = all inv
```

eg. pairwise

```
instance (CData a, CData b) => CData (a,b) where
   inv (a,b) = (inv a) && (inv b)
```

etc

Semantics of VDM type Stack

$$\left[\!\!\left[\begin{array}{l}\texttt{Stack = seq of int}\\ \texttt{~~~~~~~~inv s = forall a in set elems s \& odd(a);}\end{array}\right]\!\!\right] = \left\{\begin{array}{l}\texttt{newtype Stack = Stack \{ theStack :: [Int] \}}\\ \\ \texttt{instance CData Stack where}\\ \texttt{~~~~inv s = all odd (theStack s)}\end{array}\right.$$

- In general, VDM partial types such as `Stack` are mapped into `CData` instances.
- What about (partial) functionality?

CamilaMonad

Define `CamilaMonad`, a subclass of `Monad`

```
class Monad m => CamilaMonad m where
   -- | Check precondition
   pre :: Bool -> m ()
   -- | Check postcondition
   post :: Bool -> m ()
   -- | Check inv before returning data in monad
   returnInv :: CData a => a -> m a
```

which cares about pre-/post-conditions and invariants.

Monadic VDM translation

Example, showing *genericity* of the translation —for any `CamilaMonad m`,

```
⟦ top : Stack -> int
  top(s) == hd s
  pre not empty(s);            ⟧
```

=

```
{ top :: CamilaMonad m =>
                Stack -> m Int
  top s =
     do {
          pre (not (empty s));
          return
           (head (theStack s))
     };
```

Note the difference: our first approach was bound to

`top :: Stack -> Error Int`

How is this to work?

CamilaT monad transformer

We need a family of monads, one per evaluation mode. So, we define

```
data CamilaT mode m a =
                CamilaT {runCamilaT :: m a}
```

NB:

- `CamilaT mode m` is isomorphic to m:

  ```
  instance Monad m => Monad (CamilaT mode m) where
    return   = CamilaT . return
    ma >>= f = CamilaT (runCamilaT ma >>=
                        runCamilaT . f)
  ```

- `CamilaT` will add checking effects to a given base monad, depending on the phantom `mode` argument (*type*-indexed family of monads);

Free fall mode

Define type

```
    data FreeFall
```

and then instantiate `CamilaMonad` as follows:

```
instance Monad m =>
  CamilaMonad (CamilaT FreeFall m) where
  pre p = return ()
  post p = return ()
  returnInv = return
```

Thus

- pre-/post-conditions `p` are simply ignored
- the invariant-aware return simply does not check it

Example (free fall mode)

Taking top of an empty stack

```
testTopEmptyStack :: CamilaMonad m => m Int
testTopEmptyStack = do {
   s <- initStack ; -- create empty stack
   n <- top s ;
   return n
   }
```

In free-fall mode we get

```
> runCamilaT $ freeFall testTopEmptyStack
*** Exception: Prelude.head: empty list
```

as expected.

Fail mode

Define type

```
data Fail
```

and then instantiate `CamilaMonad` as follows:

```
instance Monad m => CamilaMonad (CamilaT Fail m) where
     pre p = if p then return ()
             else fail "Pre-condition violation"
     post p = if p then return ()
              else fail "Post-condition violation"
     returnInv a = if (inv a) then return a
                   else fail "Invariant violation"
```

Thus, when violations are detected, the standard `fail` function is used to force an immediate **fatal** error.

Running example (fail mode)

Taking top of an empty stack in fail mode will yield

```
> runCamilaT $ fatal testTopEmptyStack
*** Exception: Pre-condition violation
```

as expected.

Warn mode

Define type

```
data Warn
```

To enable reporting, we need a monad with writing capabilities, eg the standard `IO` monad:

```
instance MonadIO m => CamilaMonad (CamilaT Warn m) where
   pre p = unless p $ liftIO $ putErr "Pre-condition violation"
   post p = unless p $ liftIO $ putErr "Post-condition violation"
   returnInv a = do
     unless (inv a) $ liftIO $ putErr "Invariant violation"
     return a
instance MonadIO m => MonadIO (CamilaT mode m) where
   liftIO = CamilaT . liftIO
```

(The `unless` combinator runs its monadic argument conditionally

on its boolean argument.)

Running example (warn mode)

Taking top of an empty stack in warn mode will yield

```
> runCamilaT $ warn testTopEmptyStack
Pre-condition violation
*** Exception: Prelude.head: empty list
```

It signals out `Pre-condition violation` but carries on, later to crash as in the free-fall mode.

Running example (error mode)

(See paper for details on the `CamilaMonad` instance for this mode)

Taking top of an empty stack in error mode will yield

```
> runCamilaT $ errorMode testTopEmptyStack
*** Exception: user error Pre-condition violation
```

So, an exception is raised, but the text `user error` in the message indicates that this exception is actually catchable, and not necessarily fatal.

Fatal versus error modes

Difference between fail mode and error mode becomes clear when we try to catch the generated exceptions: compare

```
> (runCamilaT $ fatal testTopEmptyStack)
  ’catchError’  \_ -> putStrLn "CAUGHT" >> return 42
*** Exception: Pre-condition violation
```

with

```
> (runCamilaT $ errorMode testTopEmptyStack)
  ’catchError’  \_ -> putStrLn "CAUGHT" >> return 42
CAUGHT
```

Thus, exceptions that occur in error mode can be caught, higher in the call chain, while in fail mode the exception always gets propagated to the top level.

Details on elegance of solution

Clever use of the **identity function**'s polymorphism:

```
freeFall :: CamilaT FreeFall m a -> CamilaT FreeFall m a
freeFall = id

warn :: CamilaT Warn m a -> CamilaT Warn m a
warn = id
```

etc (= let the **type system** do work — *type level programming* !)

VDM Stack compiled to Haskell

```
newtype Stack = Stack { theStack :: [Int] }
instance CData Stack where inv s = all odd (theStack s)

empty :: Stack -> Bool
empty s = theStack s == []

push :: CamilaMonad m => Int -> Stack -> m Stack
push n s = do {
     pre (odd n) ;
     returnInv $ Stack (n : theStack s)
     }

pop :: CamilaMonad m => Stack -> m Stack
pop s = do {
    pre (not $ empty s) ;
    returnInv $ Stack $ tail $ theStack s
    }

top :: CamilaMonad m => Stack -> m Int
top s = do {
    pre (not $ empty s) ;
    return (head $ theStack s)
```

Summary and current work

- Formal model animation has to do with **rapid-prototyping** (= early **testing**).
- Animation prepares model for proof obligation discharge (proofs become free of stupid errors)
- “Animatographer” (=interpreter) should be as flexible as possible —thus our **evaluation modes** (new ones can be invented, cf. eg. error **logging**)
- Different modes can be used (simultaneously) for different parts of the same model
- Example —switch component testing to free-fall as soon as proof obligations have been discharged for such a component, *while keeping protecting the others’ animation*
- **Warn** mode suited for testing via **fault-injection**

Closely related work

- **VDM conversion into Gofer** (Paul Mukherjee, FME'97) —comprehensive translation strategy is based on the (fixed) `state` and `error` monads
- **VDMTools** (IFAD) —debugging and dynamic checking of invariants and pre-/post-conditions can be turned on and off individually.
- **VDM conversion into Lazy ML** (Borba & Meira, JSS 1993) —monads are not used; invariants are checked at input parameter passing time (rather than at value return time)
- **Irish VDM** (see A. Butterfield's home page) —Haskell libraries, including QuickCheck support; concern for proof obligations

Other related work

- **Programatica** —This is a system for the development of high-confidence software systems. Assertions are type-checked to ensure a base level of consistency with executable portions of the program and annotated with certificates that provide evidence of validity.
- **JCL** (Jakarta Commons Logging) —The Jakarta project of the Apache Software Foundation offers logging support in the form of a LogFactory class and a Log interface wich offers methods like fatal, error, and warn to emit messages to consoles and/or log files.

Relevance for Overture

- Software **architecture** above all —with Haskell's help
- Our monadic model for **VDM** property checking provides an answer to how such checking may be understood semantically.
- When compiling to **Java**, for instance, our monadic model so far suggests to consider using class parameters (possibly using a model of monads in Java?)
- We hope the outcome of our experiments may lead to *inspiration* for future developments in projects such as **Overture**.
- Haskell versus Java: **Scala** (F + OO) ?