Implementing Domain Specific Languages using Dependent Types and Partial Evaluation

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Introduction

This talk is about *applications* of dependently typed programming. It will cover:

- Briefly, an overview of functional programming with dependent types, using the language *Idris*.
- *Domain Specific Language (DSL)* implementation.
  - A type safe interpreter
  - Code generation via specialisation
  - Network protocols as DSLs
  - Performance data

Idris

Idris is an experimental purely functional language with dependent types (`http://www.cs.st-and.ac.uk/~eb/Idris`).

- Compiled, via C, with reasonable performance (more on this later).
- Loosely based on Haskell, similarities with Agda, Epigram.
- Some features:
  - Primitive types (`Int`, `String`, `Char`, ...)
  - Interaction with the outside world via a C FFI.
  - Integration with a theorem prover, Ivor.

Why Idris?

Why Idris rather than Agda, Coq, Epigram, ...?

- Useful to have freedom to experiment with high level language features.
- I want to see what we can achieve in practice, so:
  - Need integration with the “outside world” — foreign functions, I/O.
  - Programs need to run sufficiently quickly.

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  - *(whisper: sometimes, in the short term, it’s useful to cheat the type system)*
- Making a programming language is fun. . .

Dependent Types in Idris

Dependent types allow types to be parameterised by *values*, giving a more precise description of data.
Some data types in Idris:

```
data Nat = O | S Nat;
infixr 5 :: ; -- Define an infix operator

data Vect : Set -> Nat -> Set where  -- List with size
    VNil : Vect a O
  | (::) : a -> Vect a k -> Vect a (S k);
```

We say that `Vect` is *parameterised* by the element type and *indexed* by its length.

Functions

The type of a function over vectors describes invariants of the input/output lengths.

e.g. the type of `vAdd` expresses that the output length is the same as the input length:

```
vAdd : Vect Int n -> Vect Int n -> Vect Int n;
vAdd VNil VNil = VNil;
vAdd (x :: xs) (y :: ys) = x + y :: vAdd xs ys;
```

The type checker works out the type of `n` implicitly, from the type of `Vect`.

Input and Output

I/O in Idris works in a similar way to Haskell. e.g. `readVec` reads user input and adds to an accumulator:

```
readVec : Vect Int n -> IO ( p ** Vect Int p );
readVec xs = do { putStr "Number: ";
                  val <- getInt;
                  if val == -1 then return << _, xs >>
                               else (readVec (val :: xs));
                };
```

The program returns a *dependent pair*, which pairs a *value* with a *predicate* on that value.

The `with` Rule

The `with` rule allows dependent pattern matching on intermediate values:

```
vfilter : (a -> Bool) -> Vect a n -> (p ** Vect a p);
vfilter f VNil = << _, VNil >>;
vfilter f (x :: xs) with (f x, vfilter xs f) {
   | (True, << _, xs' >>) = << _, x :: xs' >>;
   | (False, << _, xs' >>) = << _, xs' >>;
}
```

The underscore _ means either match anything (on the left of a clause) or infer a value (on the right).

Libraries

Libraries can be imported via `include "lib.idr"`. All programs automatically import `prelude.idr` which includes, among other things:

- Primitive types `Int`, `String` and `Char`, plus `Nat`, `Bool`
- Tuples, dependent pairs.
- `Fin`, the finite sets.
- `List`, `Vect` and related functions.
- `Maybe` and `Either`
- The `IO` monad, and foreign function interface.

A Type Safe Interpreter

A common introductory example to dependent types is the type safe interpreter. The pattern is:

- Define a data type which represents the language and its typing rules.
- Write an interpreter function which evaluates this data type directly.

[demo: `interp.idr`]

A Type Safe Interpreter

Notice that when we run the interpreter on functions *without* arguments, we get a translation into Idris:

```
Idris> interp Empty test
\ x : Int . \ x0 : Int . x + x0
Idris> interp Empty double
\ x : Int . x+x
```

Idris implements `%spec` and `%freeze` annotations which control the amount of evaluation at compile time.

[demo: `interp.idr` again]

A Type Safe Interpreter

We have *partially evaluated* these programs. If we can do this reliably, and have reasonable control over, e.g., inlining, then we have a good recipe for *efficient Domain Specific Language (DSL)* implementation:

- Define the language data type
- Write the interpreter
- Specialise the interpreter w.r.t. real programs

If we trust the host language's type checker and code generator — admittedly we still have to prove this, but only once! — then we can trust the DSL implementation.

Resource Usage Verification

We have applied the type safe interpreter approach to a family of domain specific languages with *resource usage* properties, in their type:

- File handling
- Memory usage
- Concurrency (locks)
- Network protocol state

As an example, I will outline the construction of a DSL for a simple network transport protocol.

Example — Network Protocols

Protocol correctness can be verified by *model-checking* a finite-state machine. However:

- There may be a large number of states and transitions.
- The model is needed *in addition to* the implementation.

Model-checking is therefore not *self-contained*. It can verify a protocol, but not its *implementation*.

Example — Network Protocols

In our approach we construct a self-contained domain-specific framework in a dependently-typed language.

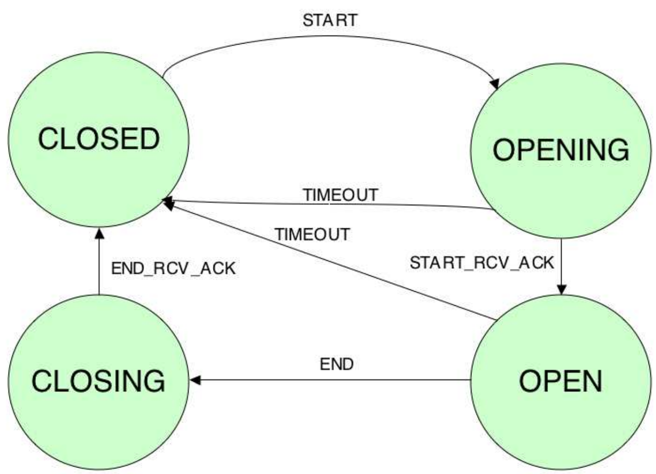
- We can express correctness properties *in the implementation itself*.
- We can express the *precise form of data* and *ensure it is validated*.
- We aim for *Correctness By Construction*.

ARQ

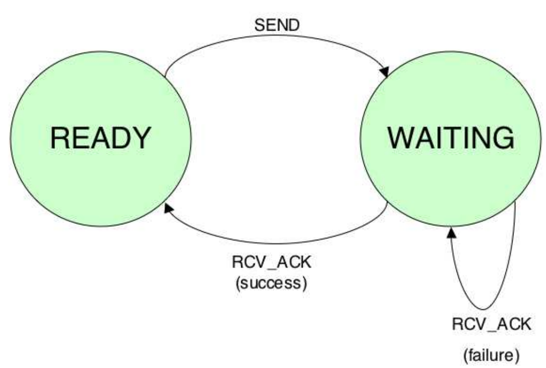
Our simple transport protocol:

- Automatic Repeat Request (ARQ)
- Separate *sender* and *receiver*
- State
  - *Session* state (status of connection)
  - *Transmission* state (status of transmitted data)

Session State



Transmission State



Session Management

We would like to express contraints on these operations, describing when they are valid, e.g.:

Command	Precondition	Postcondition
`START`	`CLOSED`	`OPENING`
`START_RECV_ACK`	`OPENING`	`OPEN` (if `ACK` received)
		`OPENING` (if nothing received)
`END`	`OPEN`	`CLOSING`
`END_RECV_ACK`	`CLOSING`	`CLOSED` (if `ACK` received)
		`CLOSED` (if nothing received)

Session Management

- `START` — initiate a session
- `START_RECV_ACK`
  — wait for the receiver to be ready
- `END` — close a session
- `END_RECV_ACK`
  — wait for the receiver to close

Sessions, Dependently Typed

How do we express our session state machine?

- Make each transition an operation in a DSL.
- Define the *abstract syntax* of the DSL language as a dependent type.
- Implement an *interpreter* for the abstract syntax.
- *Specialise* the interpreter for the ARQ implementation.

This is the recipe we followed for the well typed interpreter . . .

Session Management

- `START` — initiate a session
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  — wait for the receiver to be ready
- `END` — close a session
- `END_RECV_ACK`
  — wait for the receiver to close

When are these operations valid? What is their effect on the state? How do we apply them correctly?

Session State, Formally

`State` carries the session state, i.e. states in the Finite State Machine, plus additional data:

```
data State = CLOSED
           | OPEN PState -- transmission state
           | CLOSING
           | OPENING
```

`PState` carries the transmission state. An open connection is either waiting for an `ACK` or ready to send the next packet.

```
data PState = Waiting Seq     -- seq. no.
            | Ready Seq       -- seq. no.
```


Sessions, Formally

`ARQLang` is a data type defining the abstract syntax of our DSL, encoding state transitions in the type:

```
data ARQLang : State -> State -> Set -> Set where
   START : ARQLang CLOSED OPENING ()
 | START_RECV_ACK
     : (if_ok: ARQLang (OPEN (Ready First)) B Ty) ->
       (if_fail: ARQLang OPENING B Ty) ->
       (ARQLang OPENING B Ty)
   ...
```

[demo: `ARQdsl.idr`]

Results

We have implemented a number of examples using the DSL approach, and compared the performance of the interpreted and specialised versions with equivalent programs in C and Java.

- File handling
  - Copying a file
  - Processing file contents (e.g. reading, sorting, writing)
- Functional language implementation
  - Well-typed interpreter extended with lists

Results

Run time, in seconds of user time, for a variety of DSL programs:

Program	Spec	Gen	Java	C
fact1	0.017	8.598	0.081	0.007
fact2	1.650	877.2	1.937	0.653
sumlist	3.181	1148.0	4.413	0.346
copy	0.589	1.974	1.770	0.564
copy_dynamic	0.507	1.763	1.673	0.512
copy_store	1.705	7.650	3.324	1.159
sort_file	5.205	7.510	2.610	1.728
ARQ	0.149	0.240	—	—

Conclusion

Dependent types allow us to implement embedded DSLs *with rich specification/verification*. Also:

- We need an evaluator for type checking anyway, so why not use it for specialisation?
  - Related to MetaOCaml/Template Haskell, but free!
  - If (when?) we trust the Idris type checker and code generator, we can trust our DSL.
  - DSL programs will be as efficient as we can make Idris (i.e. no interpreter overhead).
- Lots of interesting (resource related) problems fit into this framework.

Further Reading

- "Scrapping your Inefficient Engine: using Partial Evaluation to Improve Domain-Specific Language Implementation"
  — E. Brady and K. Hammond,
  submitted 2009.
- "Domain Specific Languages (DSLs) for Network Protocols"
  — S. Bhatti, E. Brady, K. Hammond and J. McKinna,
  In Next Generation Network Architecture 2009.
- `http://www.cs.st-andrews.ac.uk/~eb/hacking/ARQdsl.html`
  — ARQ DSL implementation
- `http://www.cs.st-andrews.ac.uk/~eb/Idris`
- `http://www.cs.st-andrews.ac.uk/~eb/Idris/tutorial.html`