Haskell EDSL Implementations

Scottish Programming Languages and Verification Summer School 2019

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Haskell Take on DSLs

```
Subject:    [Haskell-cafe] What *is* a DSL?
From:       Günther_Schmidt <gue.schmidt () web ! de>
Date:       2009-10-07 15:10:58

Hi all,

for people that have followed my posts on the DSL subject this
question probably will seem strange, especially asking it now ..

Because out there I see quite a lot of stuff that is labeled as DSL,
I mean for example packages on hackage, quite useuful ones too,
where I don't see the split of assembling an expression tree from
evaluating it, to me that seems more like combinator libraries.

Thus:

What is a DSL?

Günther
```

haskell-cafe mailing list

1.	2009-10-28	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	S. Doaitse Swierst
2.	2009-10-28	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Nils Anders Daniel
3.	2009-10-22	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Robert Atkey
4.	2009-10-13	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Nils Anders Daniel
5.	2009-10-12	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Robert Atkey
6.	2009-10-12	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	S. Doaitse Swierst
7.	2009-10-12	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Sjoerd Visscher
8.	2009-10-09	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Colin Paul Adams
9.	2009-10-09	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Gregg Reynolds
10.	2009-10-08	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Colin Paul Adams
11.	2009-10-08	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	George Pollard
12.	2009-10-08	[Haskell-cafe] What *is* a DSL?	haskell-c	oleg
13.	2009-10-08	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Creighton Hogg
14.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Robert Atkey
15.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	minh thu
16.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Günther_Schmidt
17.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Don Stewart
18.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Dan Piponi
19.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Robert Atkey
20.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	minh thu
21.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Günther_Schmidt
22.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Joe Fredette
23.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Günther_Schmidt
24.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Joe Fredette
25.	2009-10-07	Re: [Haskell-cafe] What *is* a DSL?	haskell-c	Emil Axelsson
26.	2009-10-07	[Haskell-cafe] What *is* a DSL?	haskell-c	Günther_Schmidt

> *A DSL is just a domain-specific language. It doesn't imply any specific implementation technique.*
> *A shallow embedding of a DSL is when the "evaluation" is done immediately by the functions and combinators of the DSL. I don't think it's possible to draw a line between a combinator library and a shallowly embedded DSL.*
> *A deep embedding is when interpretation is done on an intermediate data structure.*

– Emil Axelsson, Chalmers University.

haskell-cafe mailing list

> *I’ve argued that every monad gives a DSL. They all have the same syntax - do-notation, but each choice of monad gives quite different semantics for this notation.*

– Dan Piponi

haskell-cafe mailing list

I've informally argued that a true DSL – separate from a good API – should have semantic characteristics of a language: binding forms, control structures, abstraction, composition. Some have type systems.
Basic DSLs may only have a few charateristics of languages though – a (partial) grammar. That's closer to a well-defined API in my books.

– Don Stewart

haskell-cafe mailing list

> *Parsec, like most other parser combinator libraries, is a shallowly embedded DSL... a Haskell function that does parsing, i.e. a function of type*
> `String -> Maybe (String, a)`
> *You can't analyse it further—you can't transform it into another grammar to optimise it or print it out—because the information about what things it accepts has been locked up into a non-analysable Haskell function. The only thing you can do with it is feed it input and see what happens.*

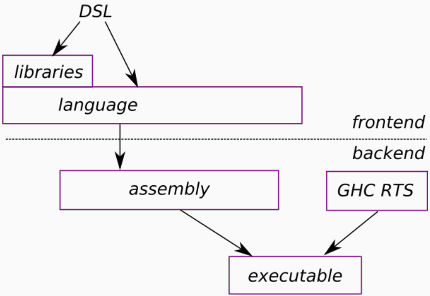
– Bob Atkey

Embeddings in Haskell

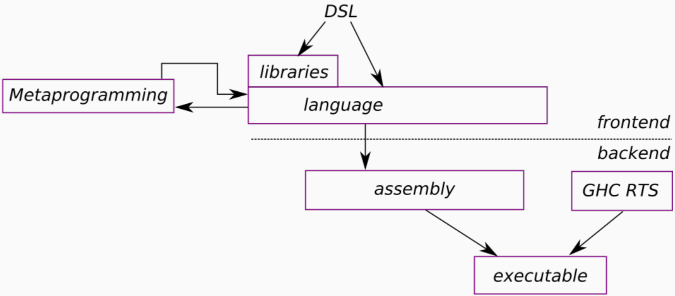
Embeddings with Haskell

- GHC gives us
  - frontend: syntax & type checking
  - interpreter: test components and small programs
- Haskell EDSL often rely on
  - higher order functions
  - type class overloading
  - monads
- Choices
  1. functions directly capture semantics of language (shallow)
  2. based on the abstract syntax of EDSL program (deep)
     - multiple interpretations *e.g.* acceleration, visualisation..

Shallow Embeddings



Compile Time Metaprogramming

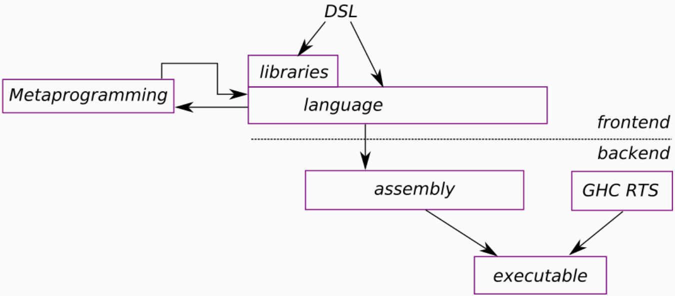


Three case studies

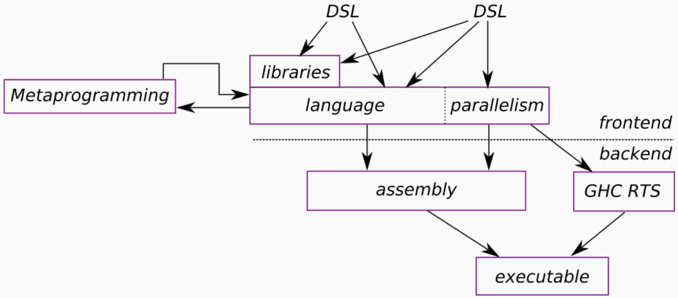
1. Repa: array processing
2. Accelerate: array processing
    - strict evaluation semantics (host language is lazy)
3. Lava: circuit description

Array Processing: Repa

Haskell Embeddings



Parallel Shallow Embedding



Repa Language

```haskell
data family Array rep sh e
data instance Array D sh e = ADelayed sh (sh -> e)
data instance Array U sh e = AUnboxed sh (Vector e)

-- types for array representations
data D   -- Delayed
data U   -- Manifest, unboxed

computeP :: (Load rs sh e, Target rt e)
         => Array rs sh e
         -> Array rt sh e
```

Ben Lippmeier et al. "Guiding parallel array fusion with indexed types". In: *Proceedings of the 5th ACM SIGPLAN Symposium on Haskell, Haskell 2012, Copenhagen, Denmark, 13 September 2012*. 2012, pp. 25–36.

Repa Example

```haskell
type Image a = Array U DIM2 a

gradientX :: Image Float -> IO (Image Float)
gradientX img = computeP
        $ forStencil2 BoundClamp img
          [stencil2|    -1  0  1
                        -2  0  2
                        -1  0  1 |]

gradientY :: Image Float -> IO (Image Float)
gradientY img = computeP
        $ forStencil2 BoundClamp img
          [stencil2|     1  2  1
                         0  0  0
                        -1 -2 -1 |]

gradMagnitude :: Float -> Image Float -> Image Float
              -> IO (Image (Float, Word8))
gradMagnitude threshLow dX dY = computeP $ R.zipWith mag dX dY
  where mag = ...
```

Repa Example

```
readImage :: String -> IO Image
saveImage :: Image -> String -> IO ()

main = do
  image1 <- readImage "input.png"
  image2 <- gradientX image1
  image3 <- gradientY image1
  image4 <- gradMagnitude thresh image2 image3
  saveImage image4 "output.png"
```

- Each `computeP` call uses static scheduler
  - assumes well balanced regular parallelism
- Monadic interface sequences parallel ”gang” schedulers
  - avoid: cache contention, overloading OS scheduler

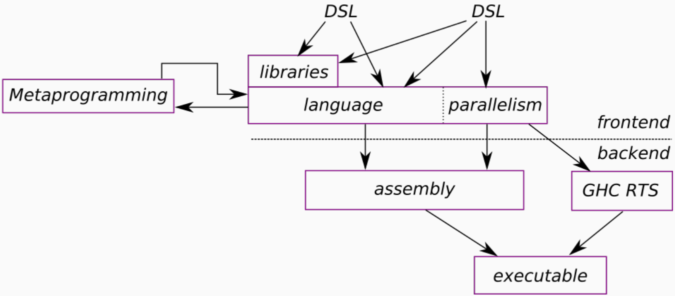
Lippmeier et al., “Guiding parallel array fusion with indexed types”.

Repa Parallelism: Use Multithreaded GHC

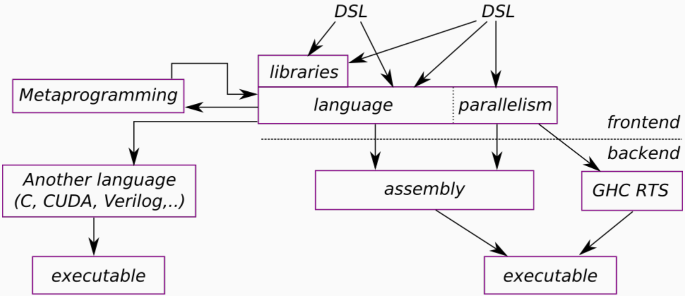
```
-- 'n' is number of threads to use
forkGang :: Int -> IO Gang
forkGang n =
  ...
  zipWithM_ forkOn [0..] -- create worker threads
    $ zipWith3 gangWorker
       [0 .. n-1] mvsRequest mvsDone

gangWorker :: Int -> MVar Req -> MVar () -> IO ()
gangWorker threadId varRequest varDone
 = do -- Wait for a request
      req     <- takeMVar varRequest
      case req of
       ReqDo action
        -> do -- Run the action we were given.
              action threadId
              ...
```

Array Processing: Accelerate

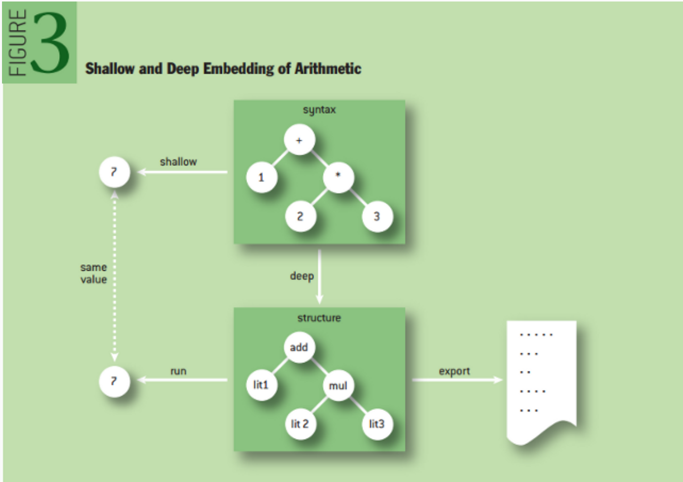
Haskell Embeddings



Parallel Deep Embedding



Deep Embeddings with Haskell



Andy Gill. "Domain-specific languages and code synthesis using Haskell". In: *Commun. ACM* 57.6 (2014), pp. 42–49.

Accelerate Literature

Material from

- Trevor McDonell's PhD thesis
- Email exchanges with Trevor

Trevor L. McDonell. "Optimising Purely Functional GPU Programs". PhD thesis. University of New South Wales, Sydney, Australia, 2015.

Accelerate

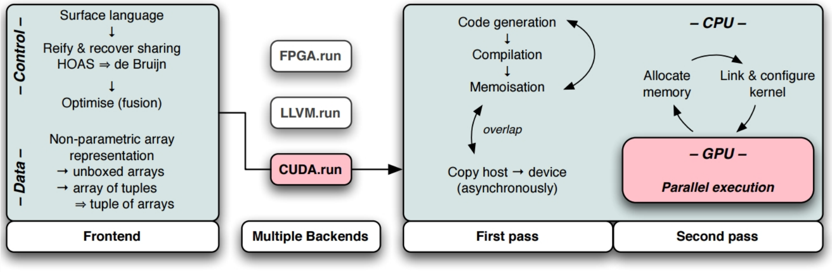
- User programs *generate* CUDA/LLVM programs at runtime

```
dotp :: Num a => Vector a -> Vector a -> Acc (Scalar a)
dotp xs ys =
  let
      xs' = use xs
      ys' = use ys
  in
  fold (+) 0 ( zipWith (*) xs' ys' )
```

- `Acc` is an Accelerate program, will produce value of type `a`
- `run` function generates code, compiles it, executes it

```
run :: Arrays a => Acc a -> a
```

Accelerate Language



McDonell, “Optimising Purely Functional GPU Programs”.

Accelerate Language Surface AST

```haskell
map     :: (Shape sh, Elt a, Elt b)
        => (Exp a -> Exp b)
        -> Acc (Array sh a)
        -> Acc (Array sh b)

zipWith :: (Shape sh, Elt a, Elt b, Elt c)
        => (Exp a -> Exp b -> Exp c)
        -> Acc (Array sh a)
        -> Acc (Array sh b)
        -> Acc (Array sh c)

stencil :: (Stencil sh a stencil, Elt b)
        => (stencil -> Exp b)
        -> Boundary (Array sh a)
        -> Acc (Array sh a)
        -> Acc (Array sh b)

-- slice, fold, backpermute, ...
```

Comiling and Executing Accelerate

- Skeletons build trees to represent array computations
- GADTs preserve embedded program's type info in term tree
- Smart constructors
  `Data.Array.Accelerate.Language`

```
map = Acc $$ Map
zipWith = Acc $$$ ZipWith
fold = Acc $$$ Fold
...
```

- Internal conversion from HOAS to de Bruijn representation enables program transformations and recovers sharing

```
-- convert array expression to de Bruijn form
-- incorporating sharing information
convertAcc :: Arrays arrs => Acc arrs -> AST.Acc arrs
```

Accelerate Internal IR

```
dotp :: Num a => Vector a -> Vector a -> Acc (Scalar a)
dotp xs ys =
  let xs' = use xs
      ys' = use ys
  in fold (+) 0 ( zipWith (*) xs' ys' )
```

Becomes:

```
Fold add (Const 0) (ZipWith mul xs' ys')
  where
    add = Lam (Lam (Body (
     PrimAdd (FloatingNumType (TypeFloat FloatingDict))
            `PrimApp`
            Tuple (NilTup `SnocTup` (Var (SuccIdx ZeroIdx))
                          `SnocTup` (Var ZeroIdx)))))
    mul = -- same as add, but using PrimMul ...
```

The generated IR **is optimised (e.g. fusion)** then compiled to object code, which is linked at runtime and executed

Skeleton Code Templates: Map (CUDA)

```
[cunit |
  $esc:("#include <accelerate_cuda.h>")
  $edecls:texIn
  extern "C" __global__ void map
  ( // types of the elements of the input/output arrays
    $params:argIn,
    $params:argOut
  ){
    const int shapeSize = size(shOut);
    const int gridSize  = $exp:(gridSize dev);
    int ix;
    for ( ix = $exp:(threadIdx dev); ix < shapeSize; ix += gridSize )
    { // gets input array element from index
      $items:(dce x .=. get ix)

      // scalar operation per element
      $items:(setOut "ix" .=. f x)
    }
|]
```

Listing 4.1 from McDonell's PhD thesis.

Skeleton Code Templates

- Accelerate now LLVM based (not CUDA)
- But same template skeleton idea
- Parallel code structure defined by skeleton templates
- Types & user defined functions added to template during code gen
- Doesn't use TemplateHaskell's quasiquotation
- Instead uses Haskell LLVM library API

Trevor L. McDonell et al. "Type-safe runtime code generation: accelerate to LLVM". In: *Proceedings of the 8th ACM SIGPLAN Symposium on Haskell, Vancouver, BC, Canada, September 3-4, 2015*. ACM, 2015, pp. 201–212.

Skeleton Code Templates: Map (LLVM)

```haskell
mkMap aenv apply =
  let
      (arrOut, paramOut)  = mutableArray @sh "out"
      (arrIn,  paramIn)   = mutableArray @sh "in"
      paramEnv            = envParam aenv
  in
  makeOpenAcc "map" (paramOut ++ paramIn ++ paramEnv) $ do
    start <- return (lift 0)
    end   <- shapeSize (irArrayShape arrIn)
    imapFromTo start end $ \i -> do
      xs <- readArray arrIn i
      ys <- app1 apply xs
      writeArray arrOut i ys
    return_

-- from 'accelerate-llvm' package
imapFromTo
  :: IR Int -> IR Int
  -> (IR Int -> CodeGen Native ()) -> CodeGen Native ()
```

Comparing Accelerate and Repa

Comparing Accelerate and Repa

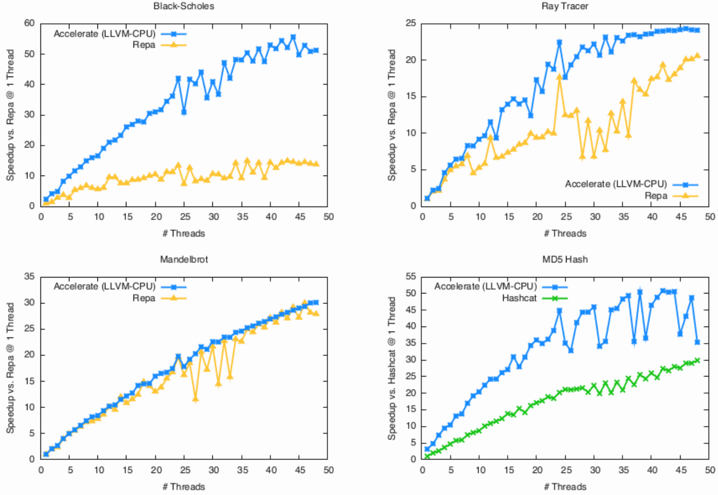
Same goals:

- Collective operations on regular multidimensional arrays
- Non-nested, flat data-parallelism
- Embed in Haskell

Achieve these goals in very different ways:

- Repa uses type indexed array representations to help GHC generate better code
- Accelerate avoids GHC's code generation altogether

Performance



McDonell et al., "Type-safe runtime code generation: accelerate to LLVM".

Benefits of Accelerate's Deep Embedding

Things you can do many with an Accelerate program:

1. Pretty print it
2. Interpret it
3. Generate & execute CUDA for GPUs
4. Generate & execute LLVM for CPUs/GPUs
5. Visualise program graph with GraphViz

Accelerate Arrays and Functions

```haskell
arr1 :: Acc (Array DIM2 Int)
arr1 = A.use $ A.fromList (Z :. 3 :. 3) [1..9]

arr2 :: Acc (Array DIM2 Int)
arr2 = A.use $ A.fromList (Z :. 3 :. 3) [10..19]

f :: Acc (Array DIM2 Int) -> Acc (Array DIM2 Int)
f = A.map (+2) . A.map (+1)

g :: Acc (Array DIM2 Int) -> Acc (Array DIM2 Int)
g = A.transpose
```

Pretty Print It

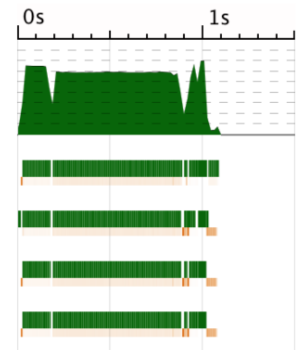
```
let program = A.zip (f arr1) (g arr2)
print program -- show it

let a0 = use (Array (Z :. 3 :. 3) [1,2,3,4,5,6,7,8,9]) in
let a1 = use (Array (Z :. 3 :. 3) [10,11,12,13,14,15,16,17,18]
in generate
 (intersect
     (shape a0)
     (let x0 = shape a1
      in Z :. indexHead x0 :. indexHead (indexTail x0)))
 (\x0 -> (2 + (1 + (a0!x0))
         , a1!Z :. indexHead x0 :. indexHead (indexTail x0)))
```

Run It

```
let program = A.zip (f arr1) (g arr2)
print print (A.run program) -- run it

Matrix (Z :. 3 :. 3)
  [ (4,10), (5,13), (6,16),
    (7,11), (8,14), (9,17),
   (10,12),(11,15),(12,18)]
```

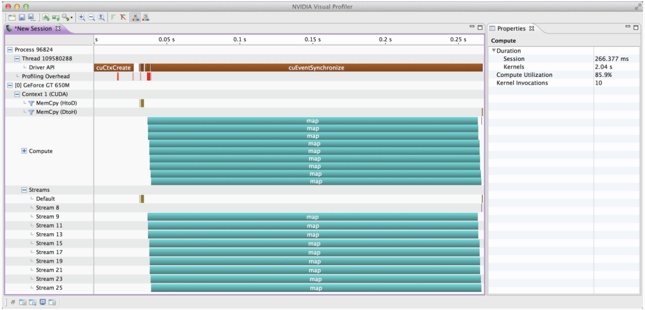
Comparison of Profiling Tooling

Repa Profiling



- Repa uses GHC runtime system
- Threadscope for profiling GHC generated parallel code
- Hence: Repa can inherit Threadscope profiling tool

Accelerate Profiling



- Accelerate doesn’t generate parallel code via GHC
- Doesn’t have access to GHC tools e.g. Threadscope
- Use NVidia profiler GPU profiling tooling instead

Figure 4.2 from McDonell’s thesis.

McDonell, “Optimising Purely Functional GPU Programs”.

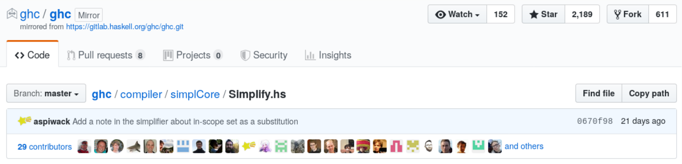
Implementation Considerations

Repa Implementation Considerations

- Good: GHC has good multicore/concurrency support
- Good: less engineering reuse GHC code generation
- Questionable: at mercy of GHC code generation

Question:

Can GHC Core be relied on for producing efficient high performance numerical code? E.g inlining and constant propagation for aggressive array fusion?



GHC Core is a **SystemF language**, not an **array processing IR**.

Accelerate Implementation Considerations

- Generate **simple LLVM IR** for the LLVM compiler
- Hope LLVM optimisations fire e.g. loop vectorisation
- LLVM/CUDA compilers assume human-written code
- Accelerate should mimic what a human would write
- Obscure LLVM code might rule out LLVM optimisations
- Don't generate SIMD instructions
    - Rely on LLVM auto-vectorisation
    - Accelerate produces code it *knows* LLVM can vectorise well
    - Accelerate tells LLVM exactly which CPU is being used
    - Ask LLVM to vectorise for this CPU

Another Domain: Circuit Description

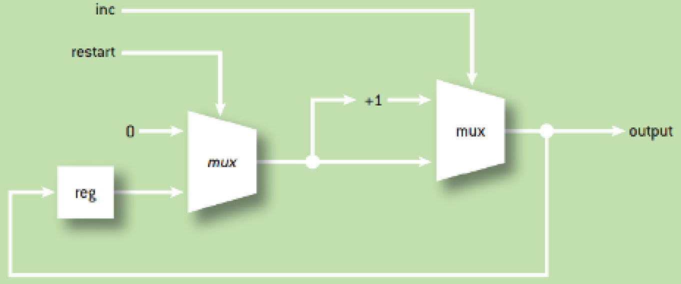
Deep EDSL: Lava

- Strongly typed EDSL for describing hardware circuits
- Deeply embedded
    - **test** circuit designs with GHCi (host language interpreter)
    - **generate** VHDL to synthesise circuits to hardware

Example from Andy Gill's *ACM Communications* paper.

Gill, "Domain-specific languages and code synthesis using Haskell".

Counting Pulses Schematic




```
counter
 :: (Rep a, Num a) => Signal Bool -> Signal Bool -> Signal a
counter restart inc = loop
  where reg = register 0 loop
        reg' = mux2 restart (0,reg)
        loop = mux2 inc (reg' + 1, reg')
```

Counting Pulses

Simulate with GHCi:

```
GHCi> counter low (toSeq (cycle [True,False,False])
1 : 1 : 1 : 2 : 2 : 2 : 3 : 3 : 3 : ...
```

Reify deep embedding:

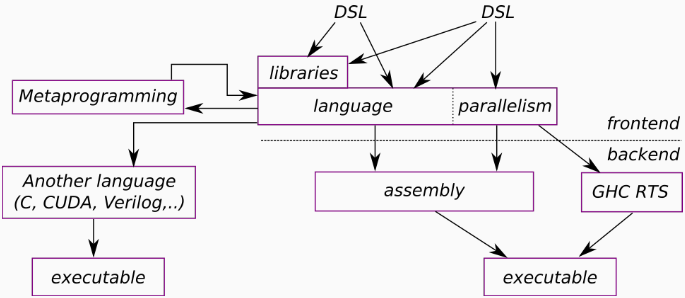
```
GHCi> reify (counter (Var "restart") (Var "inc"))
[(0,MUX2 1 (2,3)),
(1,VAR "inc"),
(2,ADD 3 4),
(3,MUX2 5 (6,7)),
(4,LIT 1),
(5,VAR "restart"),
(6,LIT 0),
(7,REGISTER 0 0)]
```

Counting Pulses

```
architecture str of counter is
  signal sig_2_o0 : std_logic_vector(3 downto 0);
  ...
begin
  sig_2_o0 <= sig_4_o0 when (inc = '1') else sig_6_o0;
  sig_5_o0 <= stf_logic_vector(...);
  sig_6_o0 <= "0000" when (restart = '1') else sig_10_o0;
  sig_10_o0_next <= sig_2_o0;
  proc14 : process(rst,clk) is
  begin
    if rst = '1' then
      sig_10_o0 <= "0000";
    elseif rising_edge(clk) then
      if (clk_en = '1') then
        sig_10_o0 <=sig_10_o0_next;
  ...
end architecture;
```

Summary

Summary



Approach	domain specific opts	host opts	language	examples
shallow	yes (rewrite rules)	yes	host	repa, HdpH-RS
deep	yes (runtime)	no	host	Accelerate, Lava
MP	yes (compile time)	yes	quasiquotes	PanTHeon

(MP = metaprogramming)