Fixing Data-flow Problems in Syntax Trees

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Introduction

- My master's thesis[1]: Call Arity vs. Demand Analysis
  - Result: Usage Analysis generalising Call Arity
  - Precision of Call Arity without co-call graphs
- Requirements led to complex analysis order
- *Specification* of data-flow problem decoupled from its *solution*

[1] `https://pp.ipd.kit.edu/uploads/publikationen/graf17masterarbeit.pdf`

Strictness Analysis

- Provides lower bounds on *evaluation cardinality*
- Is this variable evaluated at least once?
  - *Strictness*: Str ::= $S \mid L$
  - *S*trict (Yes!)
  - *L*azy (Not sure)
- Enables call-by-value, unboxing

```
main = do
  let  x = ... -- S
  let  y = ... -- S
  let  z = ... -- L
  print (x + if odd y then y else z)
```

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main = do
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  print (x + if odd y then y else z)
```

GHC's Demand Analyser

- Performs strictness analysis (among other things)
- Fuels Worker/Wrapper transformation
- Backward analysis
  - Which strictness does an expression place on its free variables?
  - Which strictness does a function place on its arguments?
- *Strictness type*: $\mathsf{StrType} = \langle \mathsf{FVs} \rightharpoonup \mathsf{Str}, \mathsf{Str}^* \rangle$

Strictness Signatures

- Looks at the right-hand side of `const` before the `let` body!
- *Unleashes* strictness type of `const`'s RHS at call sites

```
let const a b = a -- const :: ⟨[], [S, L]⟩
in const
     y              -- S
     (error "bomb.png") -- L
```

Call Context Matters

- Whole expression is strict in `z`
- Only digests `f` for manifest arity 1, can't look under lambda
- `f` is called with 2 arguments

```
let f x = -- f :: ⟨[z ↦ L], [S]⟩
      if odd x
        then \y -> y*z
        else \y -> y+z
in f 1 2
```

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```
let f x = -- f :: ⟨[z ↦ L], [S]⟩
      if odd x
        then \y -> y*z
        else \y -> y+z
in seq (f 1) 42
```

Call Context Matters

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let f x = -- f :: ⟨[z ↦ L], [S]⟩
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Call Context Matters

- Solution: Analyse RHS when incoming arity is known
- Formally: Finite approximation of *strictness transformer*
  - $\mathsf{StrTrans} = \mathbb{N} \to \mathsf{StrType}$
- Exploit laziness to memoise results?

```
let f x = -- f_1 :: ⟨[z ↦ L], [S]⟩
      if odd x
        then \y -> y*z
        else \y -> y+z
in f 1 2
```

Call Context Matters

- Solution: Analyse RHS when incoming arity is known
- Formally: Finite approximation of *strictness transformer*
  - $\mathsf{StrTrans} = \mathbb{N} \to \mathsf{StrType}$
- Exploit laziness to memoise results?

```
let f x = -- f₂ :: ⟨[z ↦ S], [S, S]⟩
      if odd x
        then \y -> y*z
        else \y -> y+z
in f 1 2
```

Recursion

- Exploit laziness to memoise approximations?
- ✗ Recursion leads to termination problems
- Rediscovered fixed-point iteration, detached from the syntax tree
- Leads to data-flow problem, solved by worklist algorithm

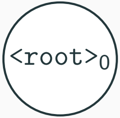
```
let fac n =
      if n == 0
        then 1
        else n * fac (n-1)
in fac 12
```

Data-flow Graph for Strictness Analysis

- Allocate nodes to break recursion
  - One top-level node
  - One node per pair of (`let` binding, incoming arity)
- Initialise worklist to top-level node
- Initialise nodes with $\perp$

```
let f 0 = const 0
    f 1 = id
    f n = f (n `mod` 2)
in f x y
```

$\Longrightarrow$



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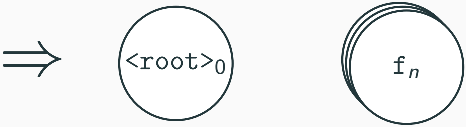

Worklist: $\{\texttt{<root>}_0\}$

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Worklist: $\{\texttt{<root>}_0\}$

Data-flow Graph for Strictness Analysis

```haskell
let f 0 = const 0
    f 1 = id
    f n = f (n `mod` 2)
in f x y
```

$\Longrightarrow$

Worklist: {<root>$_0$}

Data-flow Graph for Strictness Analysis

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let f 0 = const 0
    f 1 = id
    f n = f (n `mod` 2)
in f x y
```

$\Longrightarrow$

Worklist: $\{\}$

Data-flow Graph for Strictness Analysis

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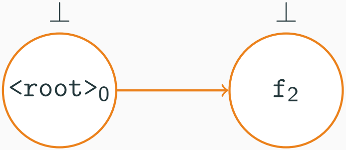

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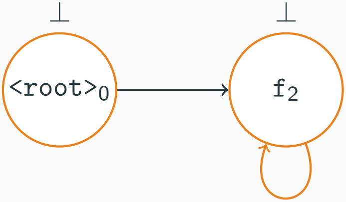

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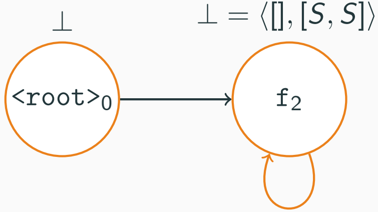

Worklist: $\{\}$

Data-flow Graph for Strictness Analysis

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    f 1 = id
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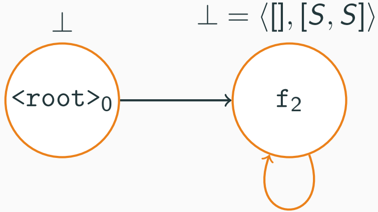
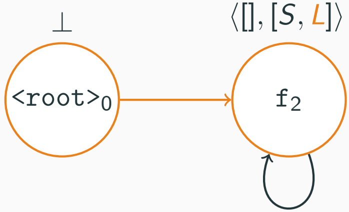


Worklist: $\{\mathtt{f}_2\}$

```haskell
let f 0 = const 0
    f 1 = id
    f n = f (n `mod` 2)
in f x y
```

$\Longrightarrow$



Worklist: $\{\mathtt{f}_2\}$

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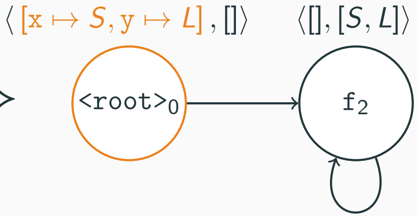

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Data-flow Graph for Strictness Analysis

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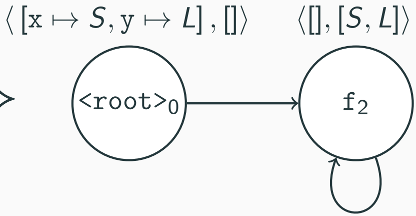

Worklist: $\{f_2\}$

Data-flow Graph for Strictness Analysis

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    f 1 = id
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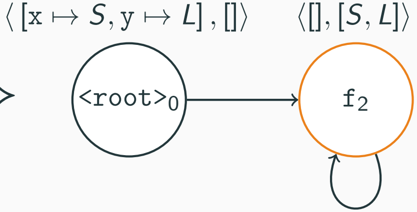
```

$\Longrightarrow$



Worklist: $\{\}$

Data-flow Graph for Strictness Analysis

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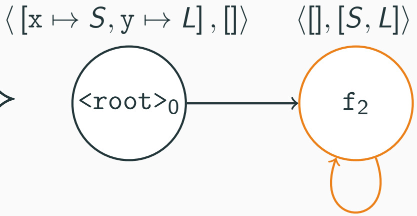

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Data-flow Graph for Strictness Analysis

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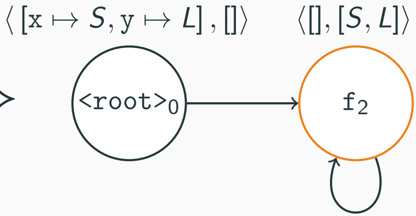

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Data-flow Graph for Strictness Analysis

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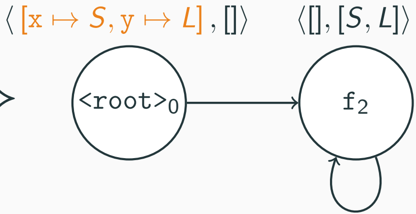

Worklist: $\{\}$

Implementation

- Hide iteration strategy behind `TransferFunction` monad
- Data-flow nodes `k`, denoting lattice `v`
- Single 'impure' primitive `dependOn`

```
data TransferFunction k v a
instance Monad (TransferFunction k v)

dependOn
  :: Ord k
  => k
  -> TransferFunction k v (Maybe v)
```

Implementation

- `DataFlowProblem` assigns `TransferFunction` and `ChangeDetector` to nodes

```
type ChangeDetector k v
  = v -> v -> Bool

data DataFlowProblem k v
  = DFP
  { transfer      :: k -> TransferFunction k v v
  , detectChanges :: k -> ChangeDetector k v
  }
```

Implementation

- `fixProblem` solves data-flow problems
- Specification as `DataFlowProblem`
- Implements fixed-point iteration strategy
  - Can use worklist algorithm, starting from a specified root set

```
fixProblem
  :: Ord k
  => DataFlowProblem k v
  -> Set k
  -> Map k v
```

Applied to Strictness Analysis

- Denote expressions by their strictness transformer
- Model points of strictness transformer separately
- Instantiate as
  `DataFlowProblem (ExprNode, Arity) StrType`
- `ExprNode`: Totally ordered, allocated as needed
  - Dictates priority in worklist
  - Performance depends on suitable priorities

Comparison to `hoopl`

- `hoopl` (**hoopl**) works on CFGs
  - Data-flow Graph
  - Basic blocks vs. transfer functions
  - Edges implicit in DSL
- Imperative languages vs. declarative languages
- ‘Operational’ rather than ‘denotational’
  - Small-step vs. compositional
- Makes (join-semi)lattice explicit
  - TODO
- Also includes a solution for transformations

Discussion

- ✓ Decouple analysis logic from iteration logic by a graph-based approach
- ✗ Coupling not as painful as it would be in imperative programs
- ✓ Still obscures intent, even obstructs ideas
- ✓ 'Hacks' such as caching of analysis results as in **dmd** between iterations for free
- ✗ Unclear how performance is affected
- ✗ Can only shine if shared concerns are actually extracted from a number of analyses

Conclusion

- Pitched an interesting idea that came out of my thesis
- Separate *specification* of data-flow problems from computing its *solution*
- Unobtrusive monadic DSL
- Future Work:
    1. (Monotone) maps with partially-ordered keys[2]
    2. Polish API, make a package[3]
    3. Testdrive and measure it in GHC

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[2] `https://github.com/sgraf812/pomaps/`

[3] `https://github.com/sgraf812/datafix`

Done

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Slides

qr_usage.jpg

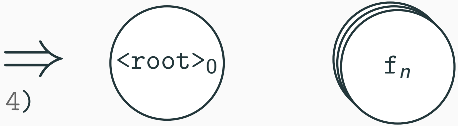
Real-world example

Bibliography

Backup

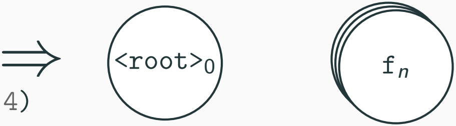
Example

```
let f 0 = const 0
    f 1 = id
    f n =
      const (f (n `mod` 2) 4)
in f x y
```



Example

```
let f 0 = const 0
    f 1 = id
    f n =
      const (f (n `mod` 2) 4)
in seq (f x) (f x y)
```



Example

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let f 0 = const 0
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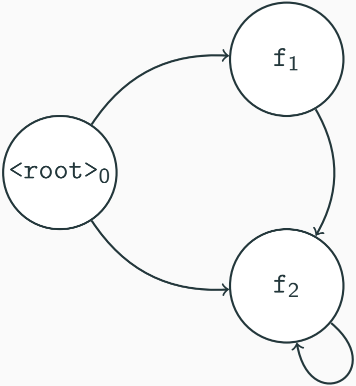

Implementation: Behind the Curtain

- `TransferFunction` is a `State` monad around `WorklistState`

```
data TransferFunction node lattice a
  = TFM (State (WorklistState node lattice ) a)
  deriving (Functor, Applicative, Monad)
```

Threading annotated expressions

- Annotated `CoreExpr`s are the reason why we do this!
- Thread it through all nodes:
  `DataFlowProblem (ExprNode, Arity) (StrType, CoreExpr)`
- Complicates change detection
  - Expressions follow AST structure
  - Possibly change when strictness type did not
  - `ChangeDetector` has to check set of changed dependencies
- Str ::= $S \mid L$ not enough for annotating functions
  - Str ::= $S^n \mid L$ with arity $n \in \mathbb{N}$
  - '`f` was called at least once, with at least n arguments'
- ... Or do it as the Demand Analyser does: Assume manifest arity for annotation
  - Be careful not to inline unsaturated wrappers!

Caching of Analysis Results due to Henglein

```
let f x =
      let g y =
            if odd y
              then g (y - 1)
              else x
      in if even x
          then g x
          else f (3*x + 1)
in f 7
```