An “Integrated Code Generator” for the Glasgow Haskell Compiler

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Classic Dataflow “Optimization,” Purely Functionally

Norman Ramsey

Microsoft Research and Tufts University

(also João Dias & Simon Peyton Jones)

Functional compiler writers
should care about imperative code

To run FP as native code, I know two choices:

1. **Rewrite terms to functional CPS, ANF; then to machine code**
2. **Rewrite terms to imperative C- -; then to machine code**

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- Access to 40 years of code improvement
- You'll do it anyway (TIL, Objective Caml, MLton)

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Functional-programming ideas ease the pain

Optimization madness can be made sane

Flee the jargon of "dataflow optimization"

- ~~Constant propagation, copy propagation, code motion, rematerialization, strength reduction~~. . .
- ~~Forward and backward dataflow problems~~
- ~~Kill, gen, transfer functions~~
- ~~Iterative dataflow analysis~~

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- Substitution of equals for equals
- Elimination of unused assignments

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- ~~**Kill, gen, transfer functions**~~
- ~~**Iterative dataflow analysis**~~

Instead consider

- **Substitution of equals for equals**
- **Elimination of unused assignments**
- **Strongest postcondition, weakest precondition**
- **Iterative computation of fixed point**

(Appeal to your inner semanticist)

Dataflow's roots are in Hoare logic

Assertions attached to points between statements:

```
{ i = 7 }
i := i + 1
{ i = 8 }
```

Code rewriting is supported by assertions

Substitution of equals for equals

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{ i = 7 }
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{ i = 7 }
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"Constant Propagation"

```
{ i = 7 }
i := 8
{ i = 8 }
```

"Constant Folding"

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“Constant Propagation”

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{ i = 7 }
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“Constant Folding”

(Notice how dumb the logic is)

Finding useful assertions is critical

Example coming up (more expressive logic now):

```
{ p = a + i * 12 }
i := i + 1
{ p = a + (i-1) * 12 }
p := p + 12
{ p = a + i * 12 }
```

Dataflow analysis finds good assertions

Example coming up (more expressive logic now):

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p := p + 12
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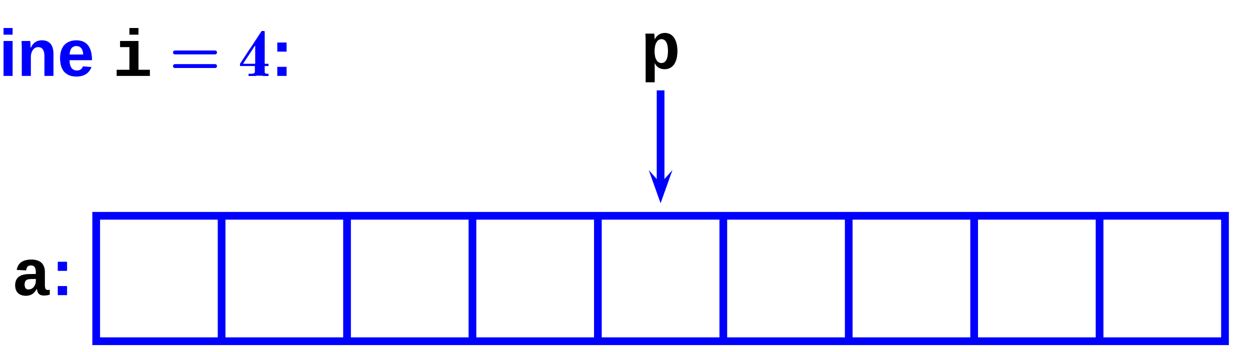
Imagine `i` $= 4$:



Example: Classic array optimization

First running example (C code):

```
long double sum(long double a[], int n) {
  long double x = 0.0;
  int i;
  for (i = 0; i < n; i++)
    x += a[i];
  return x;
}
```

Array optimization at machine level

Same example (C-- code):

```
sum("address" bits32 a, bits32 n) {
     bits80 x; bits32 i;
     x = 0.0;
     i = 0;
 L1: if (i >= n) goto L2;
     x = %fadd(x, %f2f80(bits96[a+i*12]));
     i = i + 1;
     goto L1;
 L2: return x;
}
```

Ad-hoc transformation

New variable satisfying `p == a + i * 12`

```
sum("address" bits32 a, bits32 n) {
     bits80 x; bits32 i; bits32 p, lim;
     x = 0.0;
     i = 0; p = a; lim = a + n * 12;
 L1: if (i >= n) goto L2;
     x = %fadd(x, %f2f80(bits96[a+i*12]));
     i = i + 1; p = p + 12;
     goto L1;
 L2: return x;
}
```

“Induction-variable elimination”

Use `p == a + i * 12` and `(i >= n) == (p >= lim)`:

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        x = 0.0;
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        x = %fadd(x, %f2f80(bits96[p]));
        i = i + 1; p = p + 12;
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```

Finally, `i` is superfluous

"Dead-assignment elimination" (with a twist)

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Things we can talk about

Here and now:

- **Example of code improvement ("optimization") grounded in Hoare logic**
- **Closer look at assertions and logic**

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Possible sketches before I yield the floor:

- Ingredients of a "best simple" optimizer
- Bowdlerized code
- Data structures for "imperative optimization" in a functional world

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- **Bowdlerized code**
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Hallway hacking:

- **Real code! In GHC now!**

Assertions and logic

Where do assertions come from?

Key observation:

Statements relate assertions to assertions

Example, Dijkstra's weakest precondition:

$$\boldsymbol{A}_{i-1} = wp(\boldsymbol{S}_i, \boldsymbol{A}_i)$$

(Also good: strongest postcondition)

Query: given $\{S_i\}$, $A_0 = \texttt{True}$, can we solve for $\{A_i\}$?

Answer: Solution exists, but seldom in closed form.

Why not? Disjunction (from loops) ruins everything: fixed point is an infinite term.

Dijkstra's way out: hand write key A's

Dijkstra says: write loop invariant:

An assertion at a join point (loop header)

- May be stronger than necessary
- Can prove verification condition

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My opinion: a great teaching tool

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- Bird/Wadler $\equiv$ applicative programming with equational reasoning

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Not available to compiler

Compiler's way out: less expressive logic

Ultra-simple logics!

(inexpressible predicates abandoned)

Results: weaker assertions at key points

Consequence:

- **Proliferation of inexpressive logics**
- **Each has a name, often a program transformation**
- **Transformation is usually substitution**

Examples:

$P ::= \bot \mid P \wedge x = k$ **"constant propagation"**

$P ::= \bot \mid P \wedge x = y$ **"copy propagation"**

Dataflow analysis solves recursion equations

Easy to think about least solutions:

$A_{i-1} = wp(S_i, A_i), A_{last} = \bot$ **"Backward analysis"**

$A_i = sp(S_i, A_{i-1}), A_0 = \bot$ **"Forward analysis"**

Classic method is iterative, uses mutable state:

1. **Set all** $A_i := \bot$
2. **Repeat for all** i**:**
   let $A'_{i-1} = A_{i-1} \sqcup wp(S_i, A_i)$
   If $A'_{i-1} \neq A_{i-1}$**, set** $A_{i-1} := A'_{i-1}$
3. **Continue until fixed point is reached**

Number of iterations is roughly loop nesting depth

Beyond Hoare logic: The context

Classic assertions are about program state σ

- **Example:** `{ i = 7 }` $\equiv \forall \sigma : \sigma(i) = 7$

Also want to assert about context or continuation θ

- **Example:** `{ dead(x) }` $\equiv \forall \sigma, v : \theta(\sigma) = \theta(\sigma\{x \mapsto v\})$
  (Undecidable, approximate by reachability)
  (Typically track live, not dead)

A “best simple” optimizer for GHC

(Shout if you’d rather see code)

Long-term goal: Haskell, optimized

Classic dataflow-based code improvement, planted in the Glasgow Haskell Compiler (GHC)

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The engineering question:

- **How to support 40 years of imperative-style analysis and optimization simply, cleanly, and in a purely functional setting?**

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The engineering question:

- **How to support 40 years of imperative-style analysis and optimization simply, cleanly, and in a purely functional setting?**

Answers:

- **Good data structures**
- **Powerful code-rewriting engine based on dataflow (i.e. Hoare logic)**

Optimization: a closer look

It’s about registers, loops, and arrays

Dataflow-based optimization

- **Not glamorous like equational reasoning, λ-lifting, closure conversion, CPS conversion**
- **Needs to happen anyway, downstream**

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Lesson learned: low-level optimization matters

- TIL (Tarditi)
- Objective Caml (Leroy)
- MLton (Weeks, Fluet, . . .)
- GHC?

Simple ingredients can do a lot

You must be able to

- Represent assignments, control flow graphically (at the machine level)
- Have infinitely many registers (or facsimile)
- Implement a few impoverished logics
- Solve recursion equations (dataflow analysis)
- Mutate assignments and branches

We have 5 essential ingredients

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Zipper control-flow graph

(Ramsey and Dias 2005)

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Dataflow monad

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Interleaved analysis and transformation
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. . . and a good register allocator

Design philosophy

The "33-pass compiler"

- **Small, simple, composable transformations**
- **"Existing optimizations clean up after new optimizations"**
- **Keep improving until code doesn't change**

Simple debugging technique wins big!

Limitable supply of “optimization fuel”

- Rewrite for performance consumes one unit
- On failure, binary search on fuel supply (spread over multiple compilation units)

Invented by David Whalley (1994)

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Bookkeeping in a “fuel monad”

What’s important

Things to remember

Dataflow analysis =

weakest preconditions + impoverished logic

“Optimization” is largely “equals for equals”

“Movement” is achieved in three steps:

1. **Insert new code**
2. **Rewrite code in place**
3. **Delete old code**

The compiler writer has three good friends:

- **Coalescing register allocator**
- **Dataflow-based transformation engine**
- **“Optimization fuel”**

Dataflow (from 10,000 ft)

(Shout if you prefer the zipper)

Lies, damn lies, type signatures

Logical formula is "dataflow fact"

```
data DataflowLattice a = DataflowLattice {
  bottom  :: a,
  join    :: a -> a,
  refines :: a -> a -> bool
}
```

Facts computed by "transfer function" (wp or sp):

```
type Transfer a = a -> Node -> a
```

Fact might justify a rewrite:

```
type Rewrite  a = a -> Node -> Maybe Graph
```

Bigger, more interesting lies

```
solve :: DataflowLattice a
      -> Transfer a
      -> a   -- fact in (at entry or exit)
      -> Graph
      -> BlockEnv a -- FP: {label |-> fact}

rewr  :: DataflowLattice a
      -> Transfer a
      -> a
      -> RewritingDepth
      -> Rewrite a
      -> Graph
      -> FuelMonad (Graph, BlockEnv a)
```

Simple, almost-true client: liveness

Lattice is set of live registers; join is union.

Transfer equations use traditional `gen`, `kill`:

```
gen, kill :: HasRegs a => a -> RegSet -> RegSet
gen  = foldFreeRegs extendRegSet
kill = foldFreeRegs delOneFromRegSet

xfer :: Transfer RegSet
xfer :: Node -> RegSet -> RegSet
xfer (Comment {})       = id
xfer (Load reg expr)    = gen expr . kill reg
xfer (Store addr rval) = gen addr . gen rval
xfer (Call f res args) = gen f . gen args . kill res
xfer (Return e)         = \ _ -> gen e $ emptyRegSet
```

Companion: dead-assignment elimination

Our most useful tool is dirt-simple:

```
removeDeads :: Rewrite RegSet
removeDeads :: RegSet -> Node -> Maybe Graph
removeDeads live (Load reg expr)
              | not (reg ‘elemRegSet‘ live)
              = Just emptyGraph
removeDeads live _ = Nothing
```

Combine with liveness `xfer` **using** `rewr`

Win by isolating complexity

Function `rewr` is scary (= 1 POPL paper)

Clients are simple:

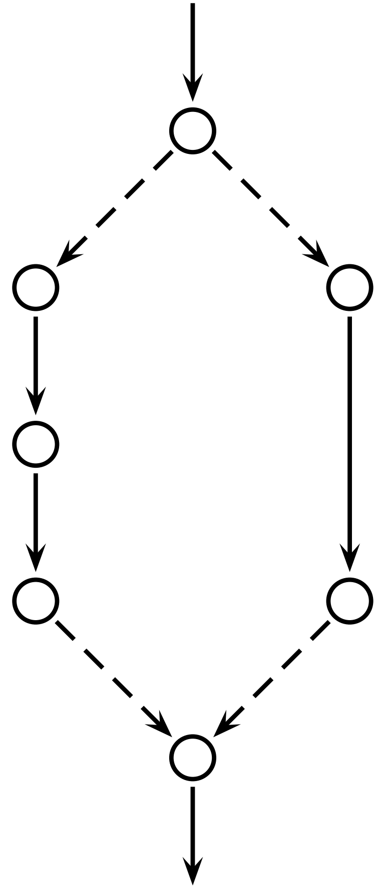
- “Impoverished logic” = “easy to understand”
- Not much code

More examples:

- Spill/reload in 3 passes (1 to insert, 2 to sink)
- Call elimination in 1 pass
- Linear-scan register allocation in 4 passes! (Dias)

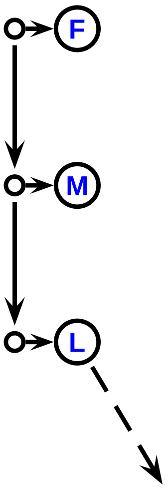
The zipper

A very simple flow graph

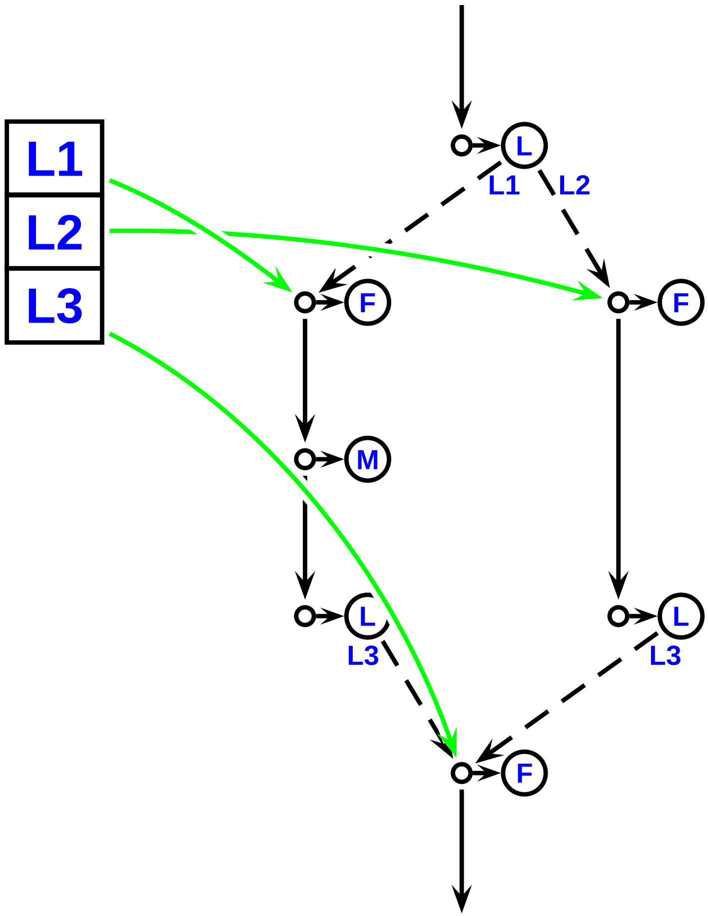


Nodes have different static types

One basic block:



Edges betweeen blocks use a finite map



Need operations on nodes

Not requiring mutation:

- Forward, backward traversal

More imperative-looking:

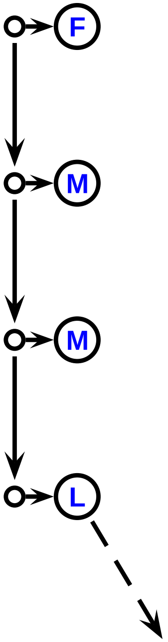
- Insert
- Replace
- Delete

All should be simple, easy, and functional

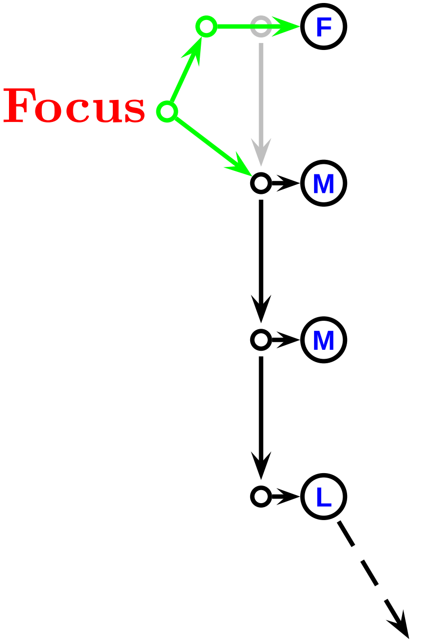
The Zipper: Manipulating basic blocks

The *focus* represents the “current” edge:

Unfocused



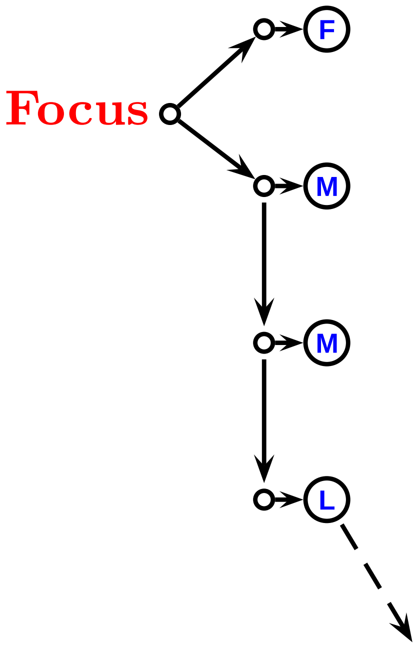
Focused on 1st edge



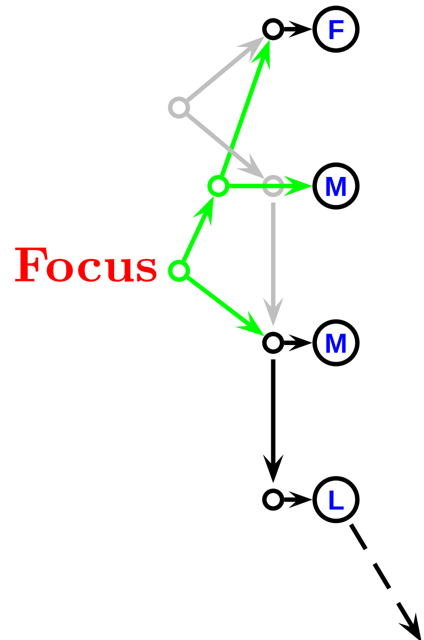
Moving the focus

Traversal requires constant-space allocation:

Focused on 1st edge



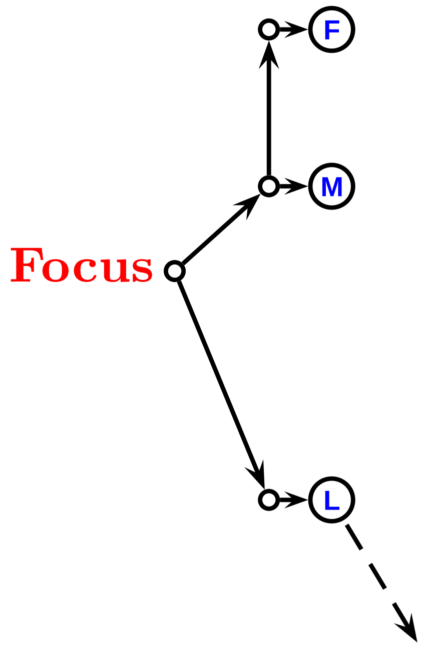
Focused on 2nd edge



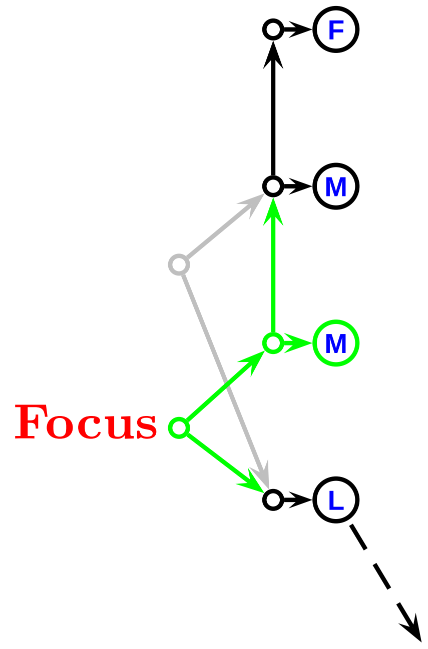
Inserting an instruction

Insertion also requires constant-space allocation:

Focused on 2nd edge



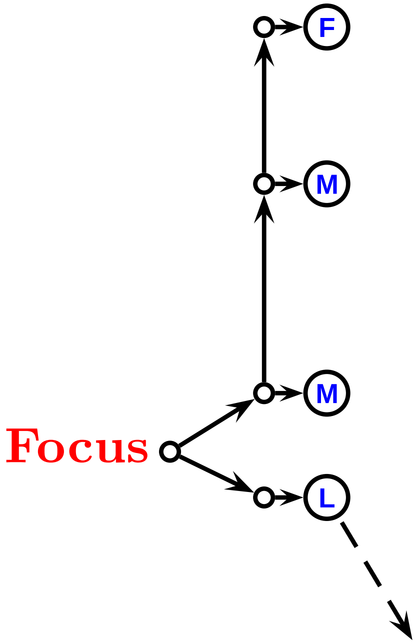
Focused on edge after new instruction



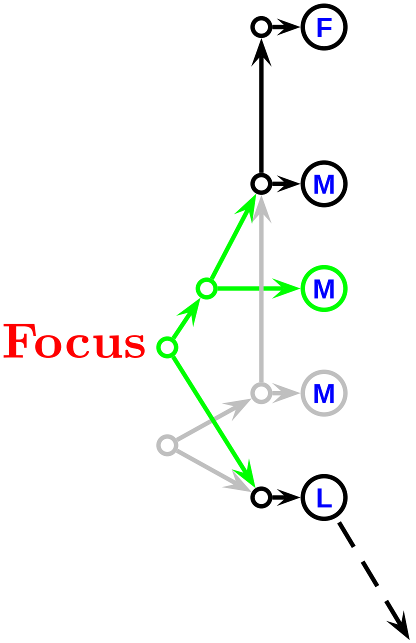
Replacing an instruction

Replacement requires constant-space allocation:

Focused after node to replace



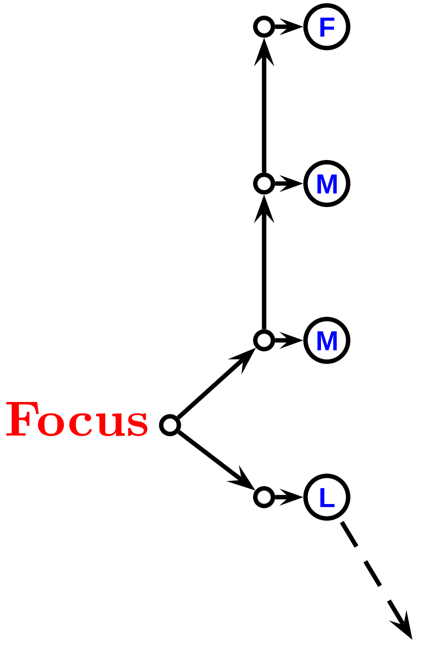
Focused after new node



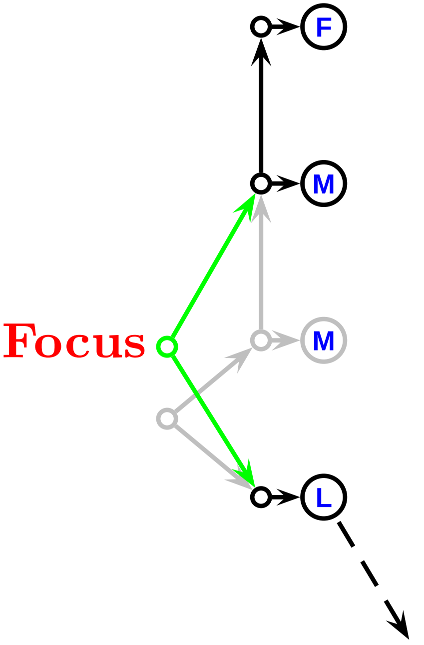
Deleting an instruction

Deletion requires (half) constant-space allocation:

Focused after delendum



Focused on new edge



Benefits of the zipper

Representation with

- **No mutable pointers (or pointer invariants)**
- **Single instruction per node**
- **Easy forward and backward traversal**
- **Incremental update (imperative feel)**

Haskell code

The zipper in Haskell

The “first” node is always a unique identifier

```
data Block m l = Block BlockId (ZTail m l)
data ZTail m l = ZTail m (ZTail m l) | ZLast (ZLast l
  -- sequence of m’s followed by single l
data ZLast l = LastExit | LastOther l
  -- ’fall through’ or a real node
data ZHead m   = ZFirst BlockId  | ZHead (ZHead m) m
  -- (reversed) sequence of m’s preceded by BlockId

data Graph m l =
  Graph (ZTail m l) (BlockEnv (Block m l))
  -- entry sequence paired with collection of blocks

data LGraph m l =
  LGraph BlockId (BlockEnv (Block m l))
  -- for dataflow, every block bears a label
```

Instantiating the zipper

```
data Middle
  = Assign CmmReg CmmExpr    -- Assign to register
  | Store CmmExpr CmmExpr    -- Store to memory
  | UnsafeCall CmmCallTarget CmmResults CmmActuals
                 -- a ’fat machine instruction’
data Last
  = Branch BlockId  -- Goto block in this proc
  | CondBranch {    -- conditional branch
        cml_pred :: CmmExpr,
        cml_true, cml_false :: BlockId
    }
  | Return          -- Function return
  | Jump CmmExpr    -- Tail call
  | Call {          -- Function call
        cml_target :: CmmExpr,
        cml_cont   :: Maybe BlockId }
            -- cml_cont present if call returns
```

Ask me about `CmmSpillReload.hs`

At every `Call` site,

- Every live variable must be saved on the "Haskell stack"

Given: C`--` with local variables live across calls

Produce: C`--` with spills and reloads,
nothing live in a register at any call

(Code produced on demand)

Beyond be dragons

Simple facts might be enough

Transfers, rewrites can compose.

Conjoin facts:

```
(<*>) :: Transfer a -> Transfer b
      -> Transfer (a, b)
```

Sum rewrites:

```
(<+) :: Rewrite a -> Rewrite a -> Rewrite a
```

Rewrite based on conjoined facts:

```
liftR :: (b -> a) -> Rewrite a -> Rewrite b
```