Debugging and Tracing Functional Programs

Olaf Chitil

University of Kent, UK

5th December 2005

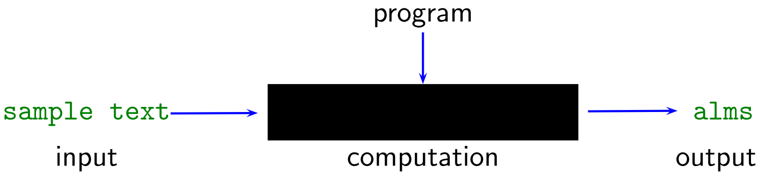
Why We Need Tracing Tools and Methods

```haskell
insert :: Ord a => a -> [a] -> [a]

insert x [] = [x]
insert x (y:ys) =
  if x > y then y : insert x ys
           else x : ys

sort :: Ord a => [a] -> [a]
sort [] = []
sort (x:xs) = insert x (sort xs)

main = getLine >>= putStrLn . sort
```



Why We Need Tracing Tools and Methods

```
insert :: Ord a => a -> [a] -> [a]

insert x [] = [x]
insert x (y:ys) =
  if x > y then y : insert x ys
           else x : ys

sort :: Ord a => [a] -> [a]
sort [] = []
sort (x:xs) = insert x (sort xs)

main = getLine >>= putStrLn . sort
```

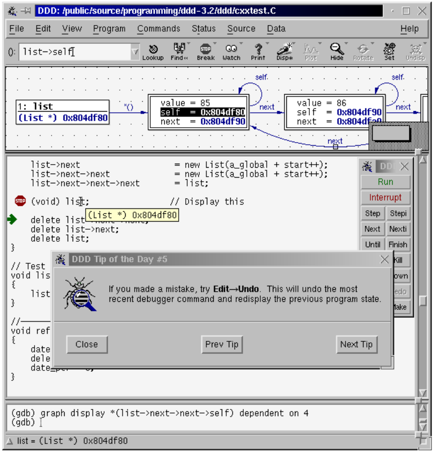
program

`sample text` → `? ? ? ? ? ? ?` → `alms`

input — computation — output

- Presence of fault already established:
  - wrong output
  - run-time error
  - non-termination
- Locate fault.
- Comprehend programs.

A stepping debugger such as DDD



The print method

- Add print statements to program.

Properties of Conventional Tracing Tools and Methods

Show at a point in time in computation a part of computation state.

- Based on one (operational) execution model.
  - program counter
  - state
  - stack
- Computation is a sequence (in time) of states.

Forward stepping of limited value:

- Fault often only noticed long after executing faulty program part.

Properties of Functional and Logic Programming Languages

- No canonical execution model.
  - various reduction semantics (small step, big step)
  - interpreters with environments (explicit substitutions)
  - also denotational semantics
- No sequential execution of statements.
  - evaluation of expressions
  - evaluation of subexpressions is independent

    `f (g 3 4) (h 1 2) (i 5) (j 3 9 3)`

Properties of Functional and Logic Programming Languages

- No canonical execution model.
  - various reduction semantics (small step, big step)
  - interpreters with environments (explicit substitutions)
  - also denotational semantics
- No sequential execution of statements.
  - evaluation of expressions
  - evaluation of subexpressions is independent
    `f (g 3 4) (h 1 2) (i 5) (j 3 9 3)`

Conclusions for Tracing

- Many semantic models as potential basis for tracing.
- Take advantage of simple and compositional semantics.
- Freedom from sequentiality of computation.

Lazy Functional Programming Languages

```
elem :: Int -> [Int] -> Bool
elem x xs = or (map (==x) xs)
```

```
elem 42 [1..]
```

Lazy Functional Programming Languages

```
elem :: Int -> [Int] -> Bool
elem x xs = or (map (==x) xs)
```

```
elem 42 [1..]
 ⇝ or (map (== 42) [1..])
```

Lazy Functional Programming Languages

```
elem :: Int -> [Int] -> Bool
elem x xs = or (map (==x) xs)
```

```
elem 42 [1..]
 ⇝ or (map (== 42) [1..])
 ⇝ or (map (== 42) (1:[2..]))
```

Lazy Functional Programming Languages

```
elem :: Int -> [Int] -> Bool
elem x xs = or (map (==x) xs)
```

```
elem 42 [1..]
 ⇝ or (map (== 42) [1..])
 ⇝ or (map (== 42) (1:[2..]))
 ⇝ or (False : map (== 42) [2..])
```

Lazy Functional Programming Languages

```
elem :: Int -> [Int] -> Bool
elem x xs = or (map (==x) xs)
```

```
elem 42 [1..]
 ⇝ or (map (== 42) [1..])
 ⇝ or (map (== 42) (1:[2..]))
 ⇝ or (False : map (== 42) [2..])
 ⇝ or (map (== 42) [2..])
```

Lazy Functional Programming Languages

```
elem :: Int -> [Int] -> Bool
elem x xs = or (map (==x) xs)
```

```
elem 42 [1..]
 ⇝ or (map (== 42) [1..])
 ⇝ or (map (== 42) (1:[2..]))
 ⇝ or (False : map (== 42) [2..])
 ⇝ or (map (== 42) [2..])
 ⋮   ⋮
 ⇝ True
```

Lazy Functional Programming Languages

```
elem :: Int -> [Int] -> Bool
elem x xs = or (map (==x) xs)
```

```
elem 42 [1..]
 ⇝ or (map (== 42) [1..])
 ⇝ or (map (== 42) (1:[2..]))
 ⇝ or (False : map (== 42) [2..])
 ⇝ or (map (== 42) [2..])
 ⋮   ⋮
 ⇝ True
```

Complex execution model:

- Complex evaluation order.
- Unevaluated subexpressions large and hard to read.
- Run-time stack unrelated to static function call structure.

Naive Printing in Haskell

Impure function `traceShow :: String -> Int -> Int`

```
insert :: Int -> [Int] -> [Int]

insert x [] = [x]
insert x (y:ys) =
  if x > y then y : (traceShow ">" (insert x ys))
           else x:y:ys

main = print (take 5 (insert 4 [1..]))
```

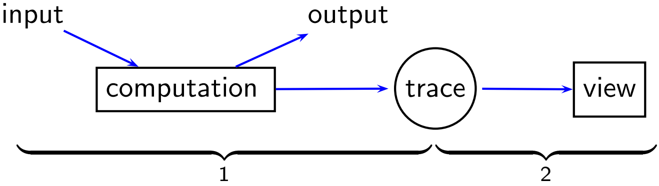
Output:

```
[1>[2>[3>[4,4,5,6,7,8,9,10,11,...
```

- output mixed up
- non-termination ⇒ observation changes behaviour

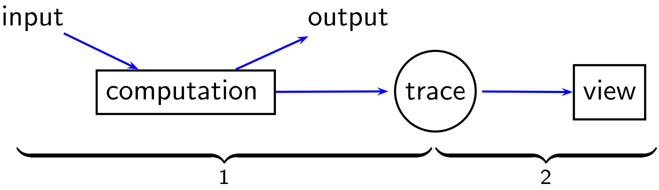
Outline

Two-Phase Tracing



Liberates from time arrow of computation.

Two-Phase Tracing

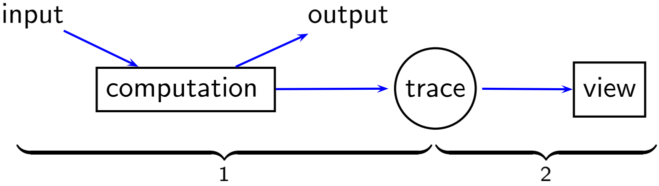


Liberates from time arrow of computation.

Trace stored in

- Memory.
- File.
- Generated on demand by reexecution.

Two-Phase Tracing



Liberates from time arrow of computation.

Trace stored in

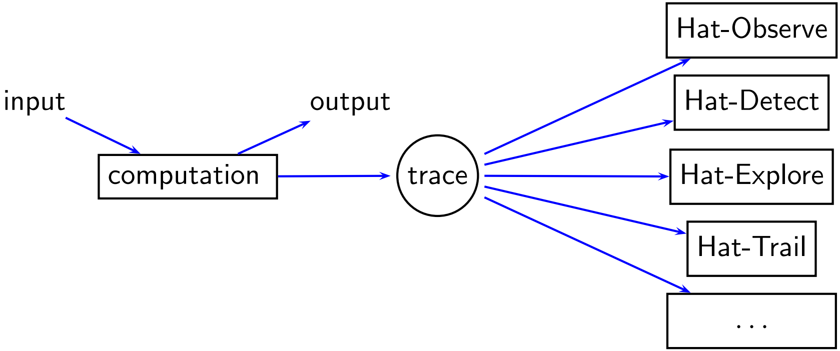
- Memory.
- File.
- Generated on demand by reexecution.

Trace Generation

- Program annotations + library.
- Program transformation.
- Modified abstract machine.

Hat

- Multi-View Tracer



- For Haskell 98 + some extensions.
- Developed by Colin Runciman, Jan Sparud, Malcolm Wallace, Olaf Chitil, Thorsten Brehm, Tom Davie, Tom Shackell, ...

Faulty Insertion Sort

```
main = putStrLn (sort "sort")

sort :: Ord a => [a] -> [a]

sort [] = []
sort (x:xs) = insert x (sort xs)

insert :: Ord a => a -> [a] -> [a]

insert x [] = [x]
insert x (y:ys) = if x > y then y : (insert x ys) else x : ys
```

Output:

```
os
```

Observation of Expressions and Functions

Observation of Expressions and Functions

Observation of function sort:

```
sort "sort" = "os"
sort "ort" = "o"
sort "rt" = "r"
sort "t" = "t"
sort "" = ""
```

Observation of function insert:

```
insert 's' "o" = "os"
insert 's' "" = "s"
insert 'o' "r" = "o"
insert 'r' "t" = "r"
insert 't' "" = "t"
```

Observation of Expressions and Functions

- Haskell Object Observation Debugger (Hood) by Andy Gill.
  - A library.
  - Programmer annotates expressions of interest.
  - Annotated expressions are traced during computation.
  - The print method for the lazy functional programmer.
- Observation of functions most useful.
- Relates to denotational semantics.

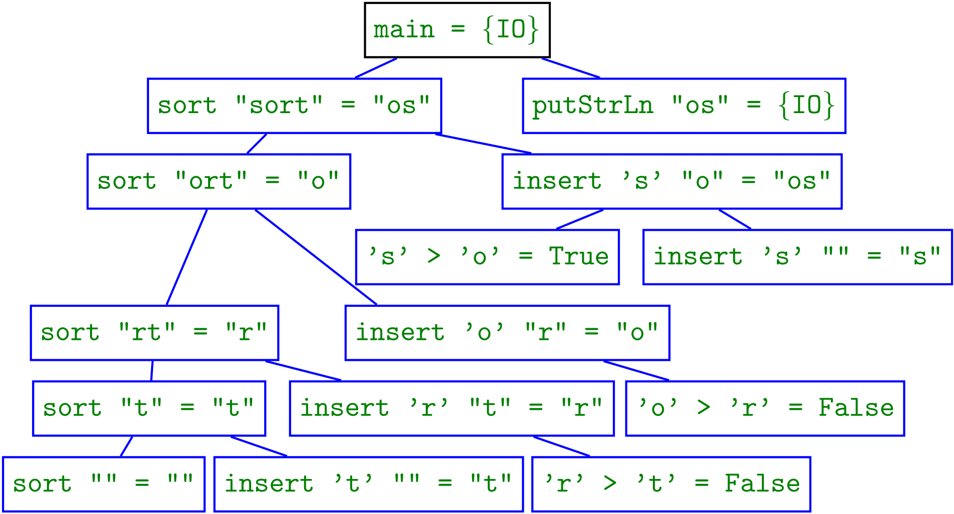
```
insert 3 (1:2:3:4:_) = 1:2:3:4:_
insert 3 (2:3:4:_) = 2:3:4:_
insert 3 (3:4:_) = 3:4:_
```

Algorithmic Debugging

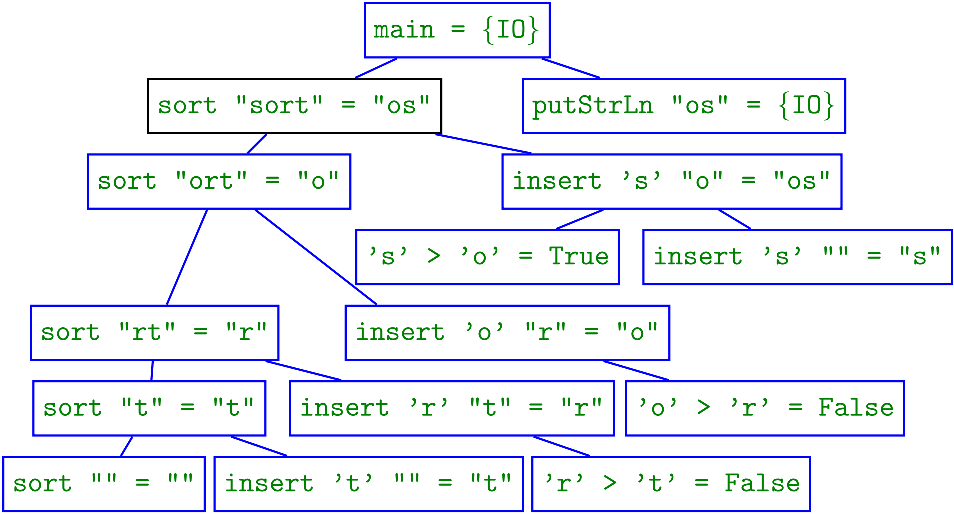
Algorithmic Debugging

```
sort "sort" == "os"
n
insert 's' "o" == "os"
y
sort "ort" == "o"
n
insert 'o' "r" == "o"
n
Bug identified:
  "Insert.hs":8-9:
  insert x [] = [x]
  insert x (y:ys) = if x > y then y:(insert x ys) else x:ys
```

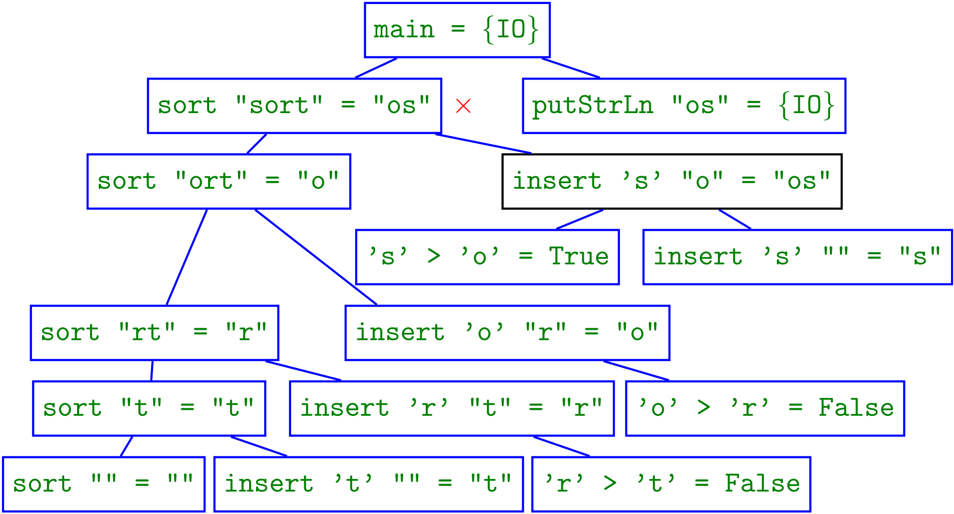
The Evaluation Dependency Tree



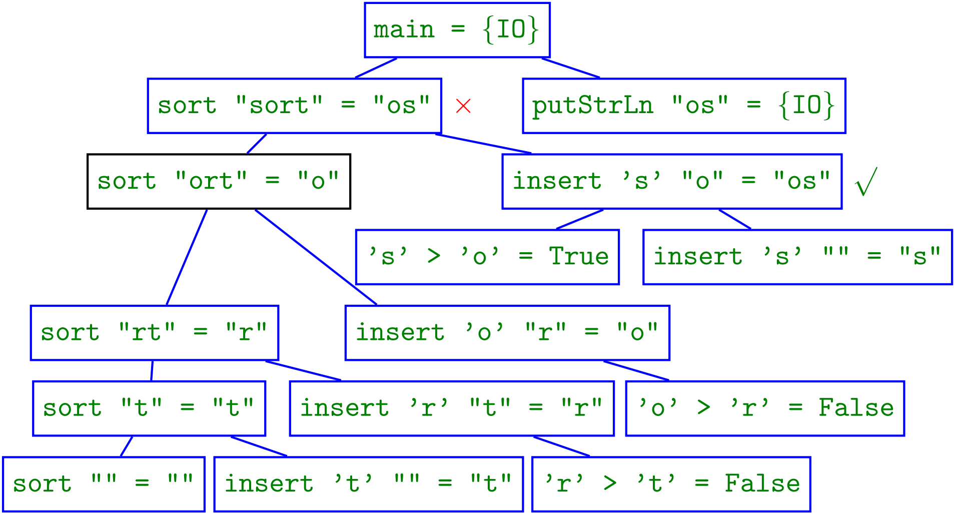
The Evaluation Dependency Tree



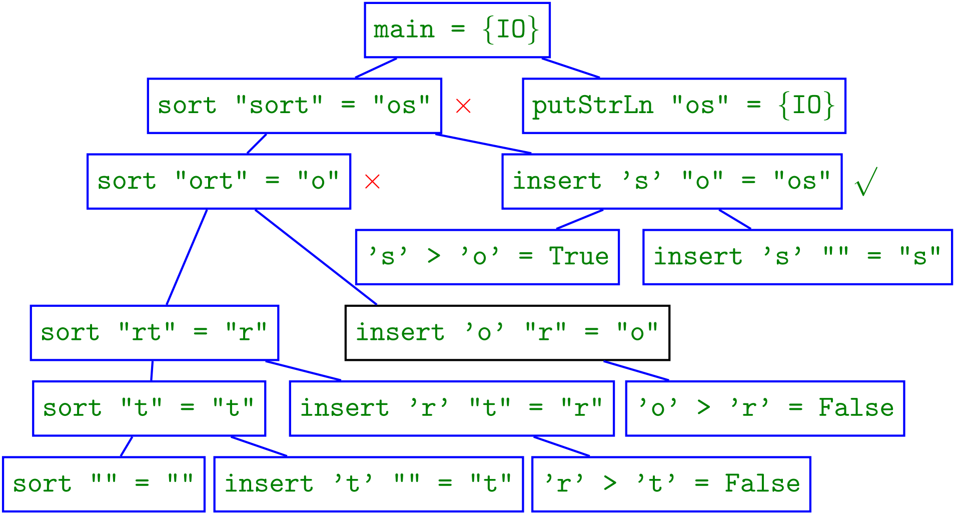
The Evaluation Dependency Tree



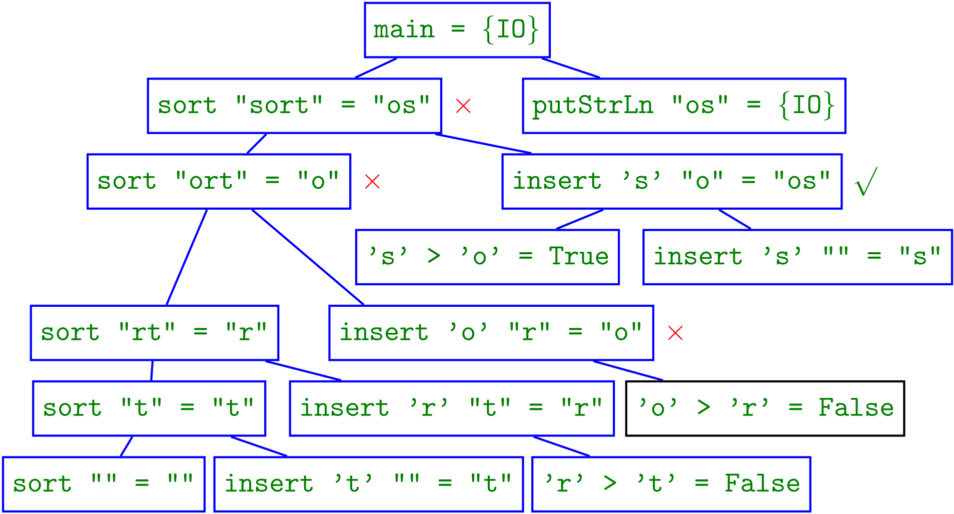
The Evaluation Dependency Tree



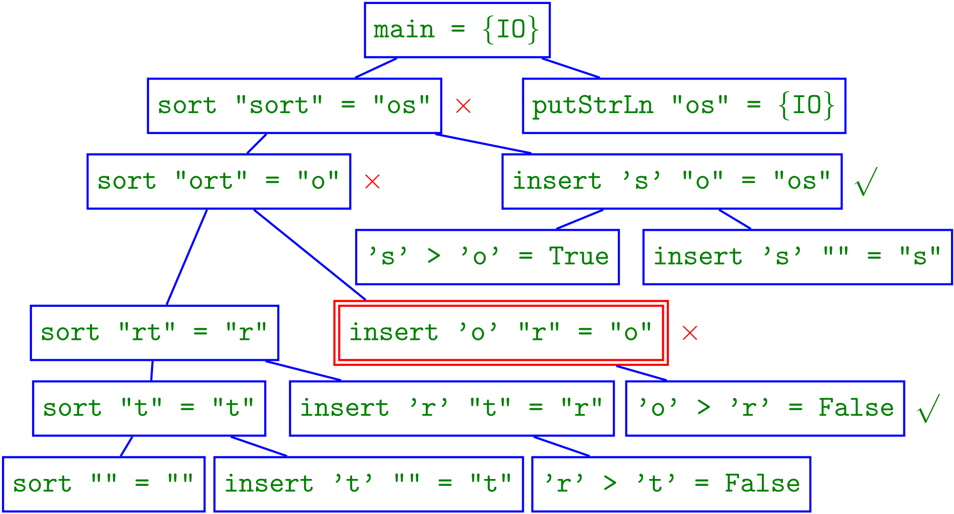
The Evaluation Dependency Tree



The Evaluation Dependency Tree



The Evaluation Dependency Tree



Algorithmic Debugging

- Shapiro for Prolog, 1983.
- Henrik Nilsson's Freija for lazy functional language, 1998.
- Bernie Pope's Buddha for Haskell, 2003.

- Correctness of tree node according to intended semantics.
- Incorrect node whose children are all correct is faulty.
- Each node relates to (part of) a function definition.

- Relates to natural, big-step semantics.

Source-based Free Navigation and Program Slicing

Source-based Free Navigation and Program Slicing

```
==== Hat-Explore 2.00 ==== Call 2/2 =======================
 1. main = {IO}
 2. sort "sort" = "os"
 3. sort "ort" = "o"

---- Insert.hs ---- lines 5 to 10 --------------------------
  if x > y then y : insert x ys
               else x : ys

sort :: [Char] -> [Char]
sort [] = []
sort (x:xs) = insert x ( sort xs )
```

Call Stack

```
Program terminated with error:
        No match in pattern.
Virtual stack trace:
(Last.hs:6)       last' []
(Last.hs:6)       last' [_]
(Last.hs:6)       last' [_,_]
(Last.hs:4)       last' [8,_,_]
(unknown)         main
```

Redex Trails

Redex Trails

```
Output: -----------------------------------------------
os\n

Trail: ------- Insert.hs line: 10 col: 25 -----------------
<- putStrLn "os"
<- insert 's' "o" | if True
<- insert 'o' "r" | if False
<- insert 'r' "t" | if False
<- insert 't' []
<- sort []
```

Redex Trails

- Colin Runciman and Jan Sparud, 1997.

- Go backwards from observed failure to fault.
- Which redex created this expression?

- Based on graph rewriting semantics of abstract machine.

Animation of Lazy Evaluation

```
Output: ------------------------------------------------

Animation: ---------------------------------------------
-> sort "sort"
-> insert 's' ( sort "ort" )
-> insert 's' ( insert 'o' ( sort "rt" ) )
-> insert 's' ( insert 'o' ( insert 'r' ( sort "t" ) ) )
-> insert 's' ( insert 'o' ( insert 'r' "t" ) )
-> "os"
```

Trusting

Trust a module: Do not trace functions in module.

- Smaller trace file.
- Avoid viewing distracting details.

  `4 + 7 = 11`

Trusting

Trust a module: Do not trace functions in module.

- Smaller trace file.
- Avoid viewing distracting details.
  `4 + 7 = 11`

A trusted function may call a non-trusted function:

```
map prime [2,3,4,5] = [True,True,False,True]
```

Trusting

Trust a module: Do not trace functions in module.

- Smaller trace file.
- Avoid viewing distracting details.
  `4 + 7 = 11`

A trusted function may call a non-trusted function:

```
map prime [2,3,4,5] = [True,True,False,True]
```

In future?

- View-time trusting.
- Trusting of local definitions.

New Ideas

- Follow a value through computation.

New Views

New Ideas

- Follow a value through computation.

Combining Existing Views

- Can easily switch from one view to another.
- All-in-one tool = egg-laying wool-milk-sow?
- Exploring combination of algorithmic debugging and redex trails.

New Views

New Ideas

- Follow a value through computation.

Combining Existing Views

- Can easily switch from one view to another.
- All-in-one tool = egg-laying wool-milk-sow?
- Exploring combination of algorithmic debugging and redex trails.

Refining Existing Views

Algorithmic Debugging:

- Different Tree-Traversal Strategies.
- Heuristics.

Why a Theory of Tracing?

- Implementations of tracing tools ahead of theoretical results.
- Correctness of tools?
- Clear methodology for using them?
- Development of advanced features?

What is a Good Trace?

Program + input determine every detail of computation.

What is a Good Trace?

Program + input determine every detail of computation.
$\Rightarrow$ Trace gives efficient access to certain details of computation.

What is a Good Trace?

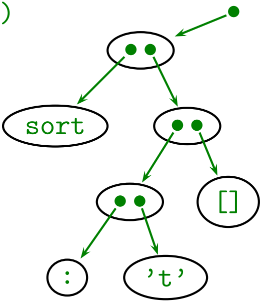
Program + input determine every detail of computation.
⇒ Trace gives efficient access to certain details of computation.

What is a computation? Semantics answers:

- Term rewriting: A sequence of expressions.
  $t_1 \longrightarrow t_2 \longrightarrow t_3 \longrightarrow t_4 \longrightarrow t_5 \longrightarrow \ldots \longrightarrow t_n$
- Natural semantics: A proof tree.

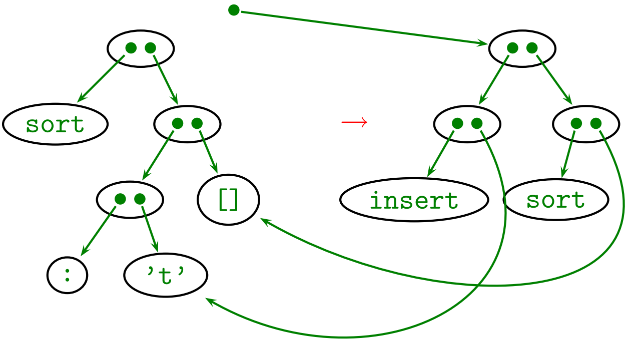
Graph Rewriting I

```
sort ('t':[])
```




```
sort [] = []
sort (x:xs) = insert x (sort xs)
```

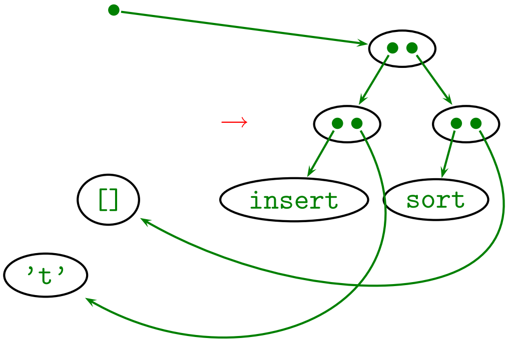
Graph Rewriting I




```
sort []     = []
sort (x:xs) = insert x (sort xs)
```

- Create new nodes for right-hand-side.
- Nodes of subexpressions are shared.

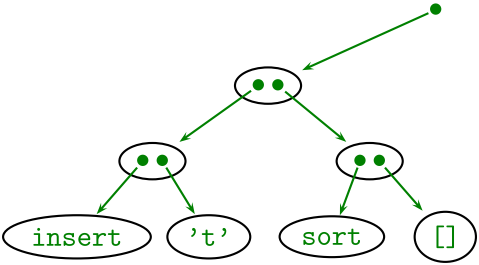
Graph Rewriting I




```
sort [] = []
sort (x:xs) = insert x (sort xs)
```

- Create new nodes for right-hand-side.
- Nodes of subexpressions are shared.
- Some old nodes become garbage.

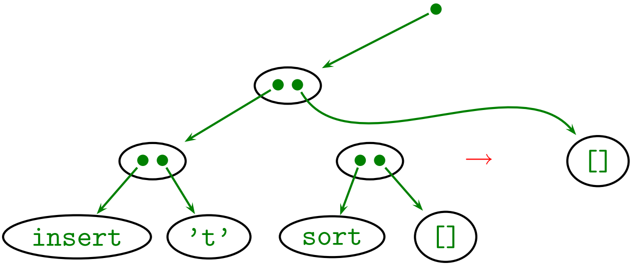
Graph Rewriting II




```
sort [] = []
sort (x:xs) = insert x (sort xs)

insert x [] = [x]
insert x (y:ys) = if x > y then y : (insert x ys) else x : ys
```

Graph Rewriting II

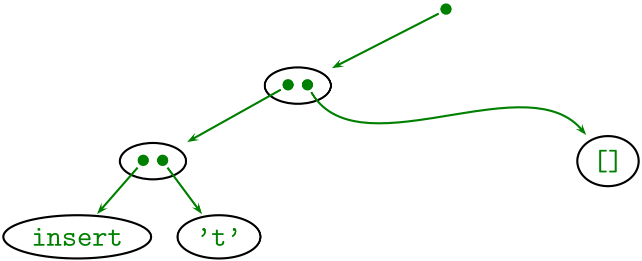



```
sort [] = []
sort (x:xs) = insert x (sort xs)

insert x [] = [x]
insert x (y:ys) = if x > y then y : (insert x ys) else x : ys
```

- Application node of redex replaced by new node.

Graph Rewriting II

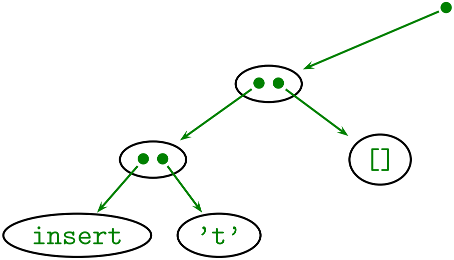



```
sort [] = []
sort (x:xs) = insert x (sort xs)

insert x [] = [x]
insert x (y:ys) = if x > y then y : (insert x ys) else x : ys
```

- Application node of redex replaced by new node.

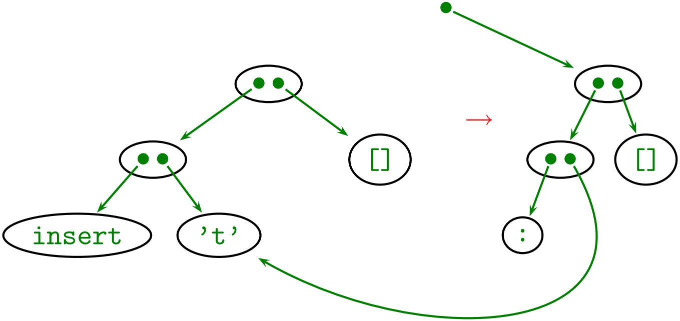
Graph Rewriting III




```
sort [] = []
sort (x:xs) = insert x (sort xs)

insert x [] = [x]
insert x (y:ys) = if x > y then y : (insert x ys) else x : ys
```

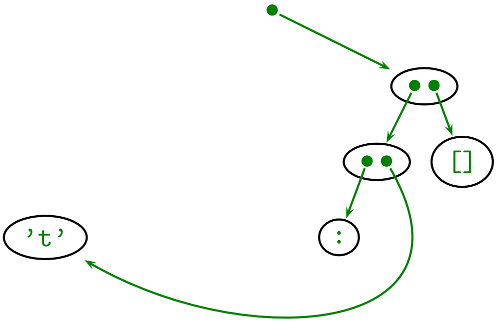
Graph Rewriting III




```
sort [] = []
sort (x:xs) = insert x (sort xs)

insert x [] = [x]
insert x (y:ys) = if x > y then y : (insert x ys) else x : ys
```

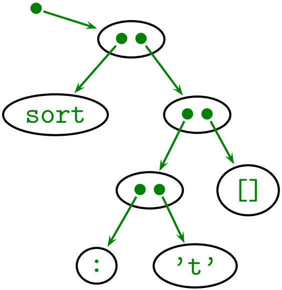
Graph Rewriting III



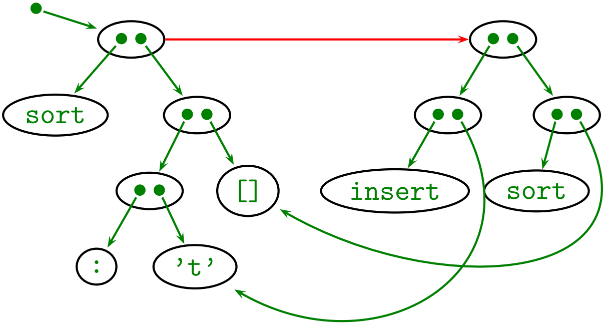

```
sort [] = []
sort (x:xs) = insert x (sort xs)

insert x [] = [x]
insert x (y:ys) = if x > y then y : (insert x ys) else x : ys
```

The Trace

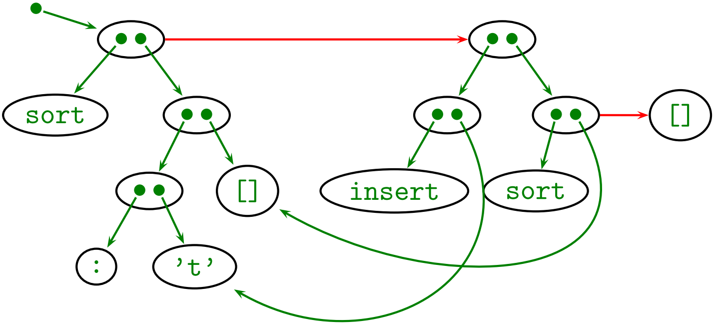


The Trace



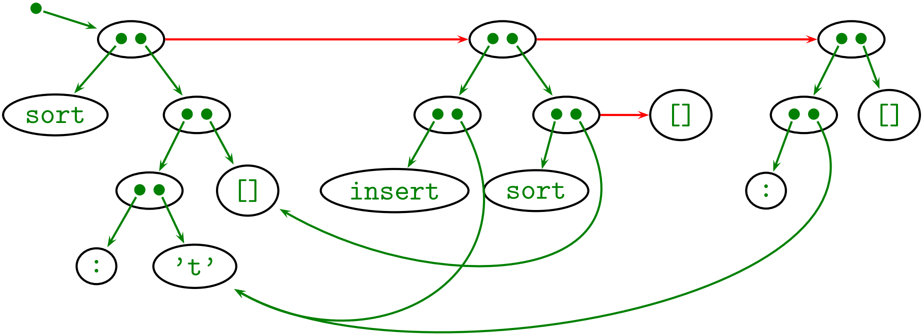
- New nodes for right-hand-side, connected via result pointer.

The Trace



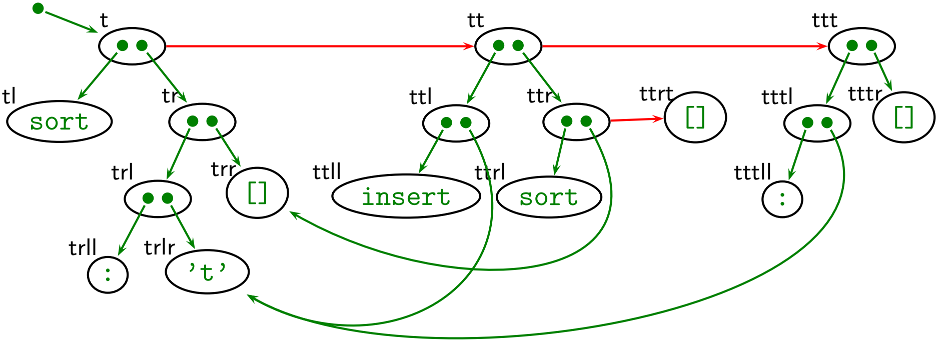
- New nodes for right-hand-side, connected via result pointer.

The Trace



- New nodes for right-hand-side, connected via result pointer.

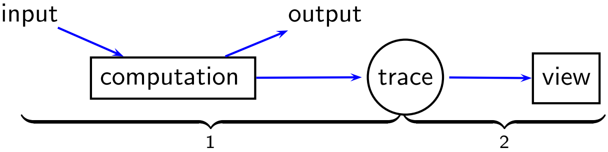
The Trace



- New nodes for right-hand-side, connected via result pointer.
- Unique node names
  - Node names independent of evaluation strategy.
  - No graph isomorphism needed.
  - Node name encodes history (parent redex, also reduct).

Summary

- Two-Phase Tracing.



  Liberates from time arrow of computation.
- There exist many useful different views of a computation.
  - Observation of Functions
  - Algorithmic Debugging
  - Source-based Free Navigation
  - Redex Trails

    ...
- Semantics.
  - Inspire views.
  - Enable formulation and proof of properties.
  - But do not answer all questions.
- Still much to explore.