```
data Tree a = E | N (Tree a) a (Tree a) deriving (Show)

task :: Integer -> [Tree Integer] -> Tree b
     -> (Integer,[Tree Integer],[Tree b],Tree Integer)
task n ~rs          E          = (n  ,rs,[]   ,E)
task n ~(r':l':rs) (N l x r) = (n+1,rs,[l,r],N l' n r')

taskM :: Integer -> [Tree b] -> [Tree Integer]
taskM n []     = []
taskM n (t:ts) = rs'++[t']
  where
    (n',rs',tp',t') = task n ts' t
    ts'             = taskM n' (ts++tp')

bfnum :: Tree a -> Tree Integer
bfnum t = head $ taskM 1 [t]
```

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Visualising Observations of Haskell Program Runs

Claus Reinke

Computing Lab, University of Kent at Canterbury

```
data Tree a = E | N (Tree a) a (Tree a) deriving (Show)

.. code as before ..

someTree = N (N (N E 0 E) 1 (N E 0 E)) 2 (N (N E 0 E) 1 (N E 0 E))

main = print $ bfnum someTree


{- compare input tree and program output:

N (N (N E 0 E) 1 (N E 0 E)) 2 (N (N E 0 E) 1 (N E 0 E))
N (N (N E 4 E) 2 (N E 5 E)) 1 (N (N E 6 E) 3 (N E 7 E))

but setting up a sensible testbed isn't always that easy;
we might want to test parts of a program, but in their
original context!
-}
```

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```
import Observe

data Tree a = E | N (Tree a) a (Tree a) deriving (Show)

instance Observable a => Observable (Tree a) where
  observer E         = send "E" (return E)
  observer (N l x r) = send "N" (return N << l << x << r)

.. code as before ..

main = printO $
  observe "after" $ bfnum $ observe "before" $ someTree
```

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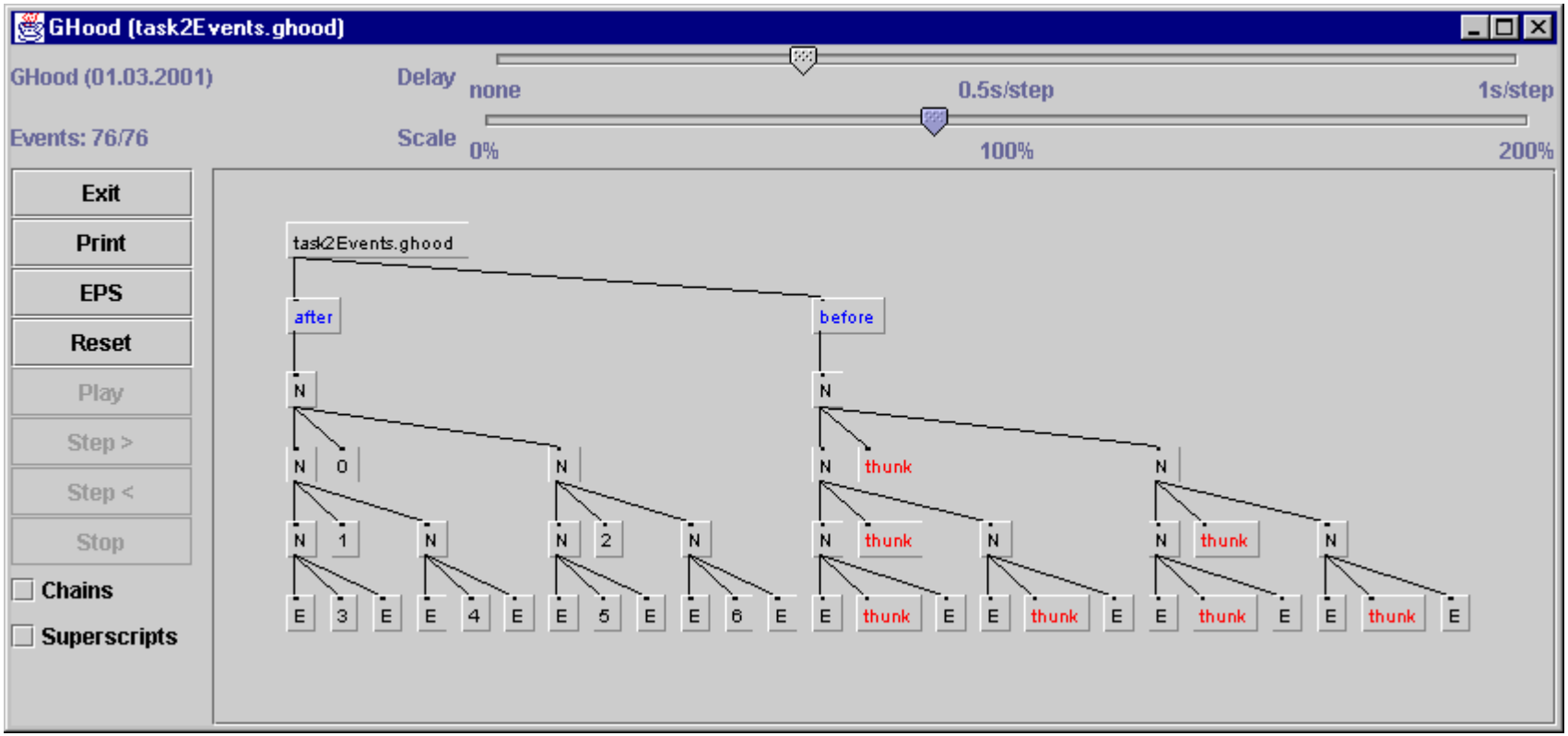

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Declarative versus imperative style

- *declarative programs* tend to *describe* the *"what?"* of computations, leaving the *"how?"* implicit
- *imperative programs* tend to *prescribe* the *"how?"* of computations, leaving the *"what?"* implicit

functional programs* tend to *emphasise a descriptive style* while also *indicating possible ways of computing

- this is a useful compromise, supported by experience:
  - *1. get it right* (only if necessary: *2. make it efficient*)
  - surprisingly often, compilers can do a good job of 2.
  - sometimes, they need a little help..

The implicit "how"

- Functional programmers have tried to leave operational aspects to "clever" compilers, as far as possible..
- ***compilers have become quite good*, but**
  - **they *rarely change your algorithms/data structures***
  - **they *can't guess what you want* (value of resources?)**
- most operational aspects are still handled implicitly:
  0. programs describe algorithms
  1. compilers "derive" code directly from the algorithms in your programs, using some operational semantics
  2. compilers "optimise" within algorithms/data structures
  3. low-level profilers help you to see the resource usage
  4. you change your program and try again..

  $\Rightarrow$ *unknowns in 1&2, declarativeness compromised by 4!*

The "what" of "how" - part I *(specification)*

- *Programs = declarations + operational aspects*
- operational aspects implicit ⇒ compiler chooses defaults
  - one set of defaults is not always adequate
  - should we really try to guess those defaults?

  ⇒ options & pragmas, but do they need to be imperative?
  (who knows appendix E.3 to the Haskell report?)
  - should we really change the declarations to get an indirect handle on the operational aspects?

- ***improved declarative (?) means to describe operational aspects of functional programs seem to be called for, as well as means to instantiate declarative programs with some specific operational properties***

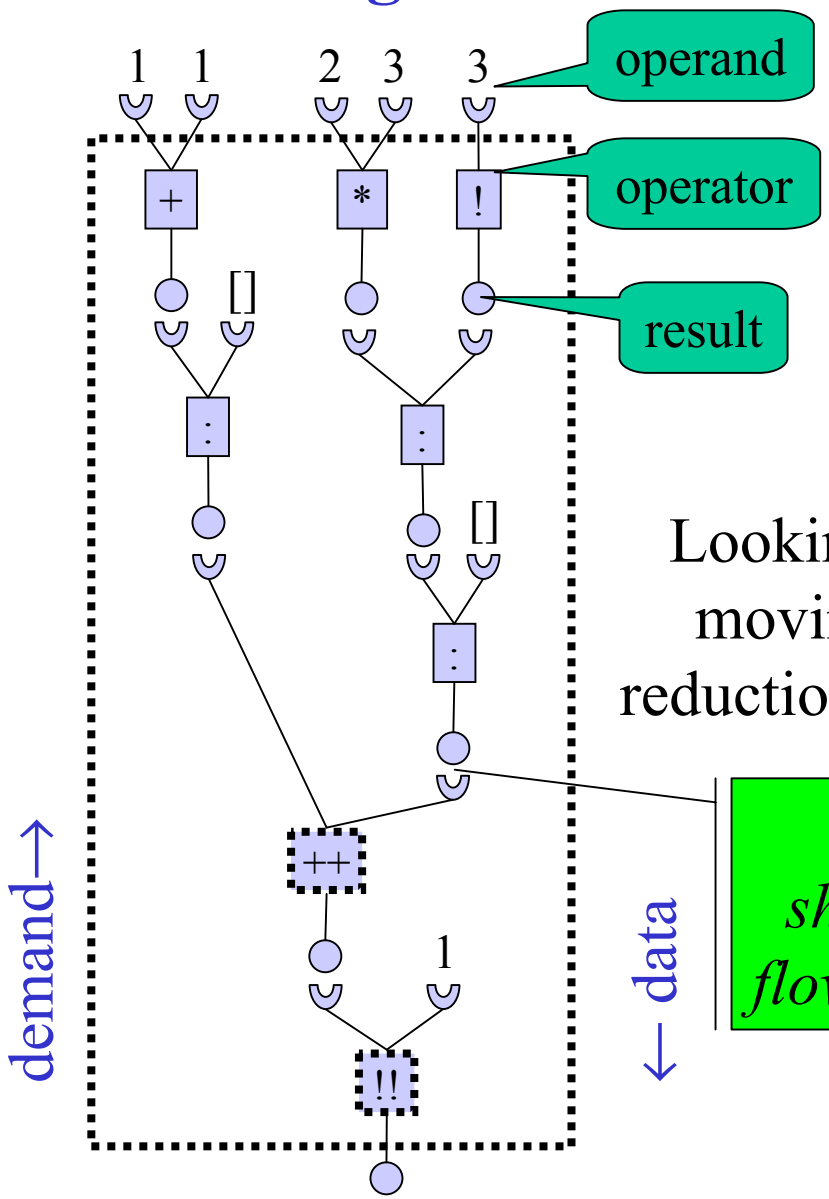
(aspect-oriented programming has some ideas on the latter)

The "what" of "how" – part II *(understanding)*

- *Programs = declarations + operational aspects*
  (similar to logic + proof theory)
- we need a better understanding of program behaviour
  - what are operational aspects? (space/time use during compilation/execution, strictness, dependencies,..)
  - can they be isolated from declarative aspects?
  - *high-level operational semantics* would be useful
  - the problems are dynamic in nature, so *high-level animations of program behaviour* would be a nice way to gain insights
  - ..

$\Rightarrow$ lots of other interesting issues, but this talk is only about the *visualisation of program behaviour*

Program behaviour: flow versus rewriting



redex

([1+1]++[2*3,3!])!!1

↓

reduct

((1+1):([]++[2*3,3!]))!!1

↓

([]++[2*3,3!])!!(1-1)

↓

Looking glass, moving over reduction sequence

([]++[2*3,3!])!!0

↓

[2*3,3!]!!0

↓

2*3

↓

6

← reduction

Probe, showing data flowing through

different views, leading to tools focussing of different aspects

From reduction traces to flow observations, in a few easy steps

- All Haskell implementations support the non-standard

```
trace: String -> a -> a
-- output first parameter, return second parameter
-- a labelled polymorphic identity function?
```

- simple idea of tracing reduction sequences:
  - use `trace` to tag redices with `String` labels
  - runtime system outputs label when redex is reduced
  - the resulting trace of redex labels gives an indication of what reduction sequence was followed

Some problems with `trace`

P1: *where to get sensible trace labels from?*

- compute label from labelled redex (and its context)
- extra code to embed useful information into trace labels
- we're getting closer to debugging by print statements..

P2: *non-strict evaluation of functional programs is quite unlike sequential, in-order execution of imperative code.* Program traces can be very difficult to read.. (e.g., evaluation dependencies can lead to nested labels!)

P3: *replacing constant `String` labels by `String`-valued expressions could change the program under inspection!* As a typical example, `(showTrace s)` changes strictness:

```
showTrace :: Show a => String ->a -> a
showTrace s a = trace (s++(show a)) a
```

Interlude:
Side-effecting pseudo-functions for i/o, again?

- P2 is just an instance of the *general conflict between i/o by side-effect*, as in `trace`, *and non-strict evaluation order*.
- The general solutions *make the sequencing of i/o operations explicit as part of program results*.
- We can't use any of the general solutions here:

we want to change the program under inspection as little as possible!

- i/o and tracing look similar but are actually quite different:
  - functional i/o tries to add i/o to functional programs
  - tracing tries to add i/o to functional language implementations

From `trace` to `observe` (outline)

P1: *where to get sensible labels from?*

- *provide the extra code* for gathering information about parameters *in a library*, *returning labels to a tag-role*
- use type classes to provide versions of *generic code*

P2: *confusing output in evaluation order*

- don't output observations in evaluation order
- use labels to *group related observations* together

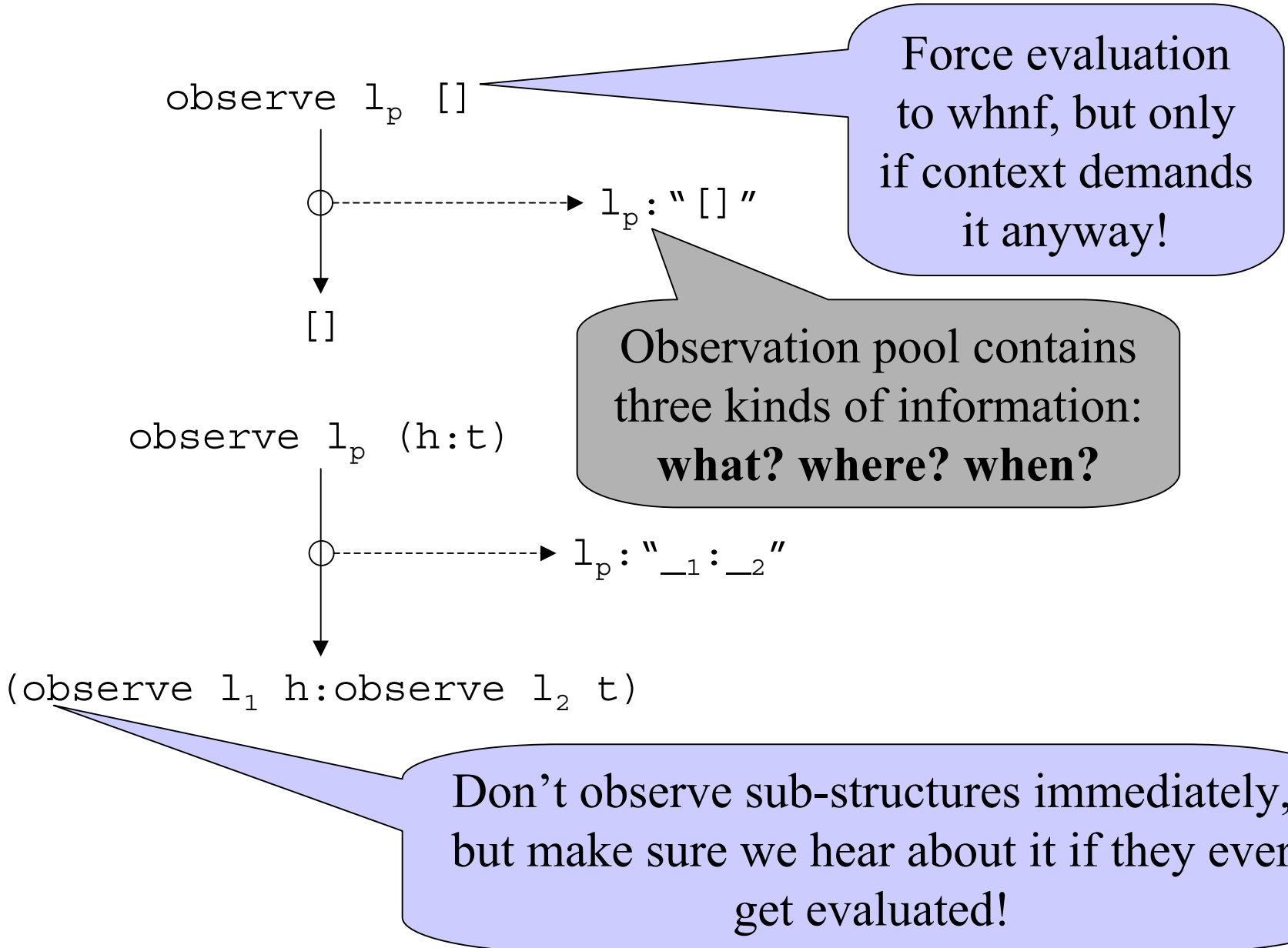
P3: *danger of changing program properties*

- factoring observation code into a library localises possible problems and allows to reuse code that works
- mere inspection of data can introduce new demands for evaluation, so *be careful not to inspect anything unless the original program inspects it as well!*

Behind the scenes

- `unsafePerformIO :: IO a -> a`
- Usually seen as side-effecting pseudo function for dirty work that may need to be done in libraries: use normal IO, then „pretend that nothing has happened“ (prefix `unsafe` indicates proof obligation)
- Just what we need for tracing, observing, and debugging?
  - can implement `trace`:
    ```
    trace l a = unsafePerformIO (putStr l >> return a)
    ```
  - can also maintain state of unique label supply, easing construction of partial data structures from observations
  - could even support user interaction
- Can also be seen as an extension hook in the evaluation mechanism, programmable in Haskell itself!

Observing lists (pseudo-code)

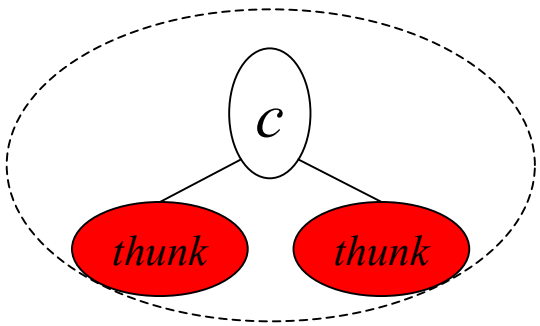


Observations

- Observations form labelled trees, built up incrementally
- At each step, observation trees represent partial knowledge of data structures passing through observation points
- Life-time of a node:

as yet unknown part, not yet under inspection

as yet unknown part, currently under inspection



partially known structure, as yet unknown parts

Hood/Ghood - variations of a theme

- The vanilla version of Hood consists of the library Observe
  - *observations are collected, grouped and pretty-printed*
  - very useful for probing data-flow in your programs, but it only uses the "*what*" and "*where*" information
- Hood in nhc98 comes with a textual observation browser
  - all advantages of vanilla version, plus use of "*when*" information for *animation* (of structure refinement)
  - doesn't work so well when observing bigger structures: lots of scrolling, no scaling, no survey view
  - text wouldn't be visible in smaller scale, and structure gets lost due the form of pretty-printing used
- Ghood is a *graphical observation browser*..

GHood demos

- GHood as a stand-alone browser, started by a Haskell evaluator or from the commandline
- GHood as an applet in webpages
- Current development of GHood focusses on
  - How to capture dynamic info in static snapshots?
  - Visualising evaluation dependencies
  - Replacing scrollbars and scaling-slider with more suitable forms of control (scrollbox, auto-scaling)
  - Upgrading to structure-preserving tree layout algorithm
  - *..lots of other open roads to follow..*
- Some ideas that don‘t quite work: fading colours, scrollbars, life-time maps (visual or textual), ..

Preliminary conclusions

- Animating Hood observations using a Java-based browser allows for portable **visualisation of program behaviour**, **even in online documentation of functional programs!** *[but using Java isn't problem-free]*
- Animation exploits the information represented by the relative ordering of observations, enabling **high-level observations of dynamic program properties**.
- **Graphical visualisation** offers the usual advantages of scale over textual methods (when labels are no longer readable, structure should be recognizable after layout). *[but standard user interface issues come into play]*
- **User feedback has been encouragingly positive so far**.
- Please try it yourselves: http://www.cs.ukc.ac.uk/people/staff/cr3/toolbox/haskell/GHood