

Functional Programming

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Lazy Evaluation

To execute a program, *Haskell reduces expressions to values*.
Haskell uses **normal order reduction** to select the next expression to reduce:

- The *outermost* reducible expression (the so-called *head redex*) is reduced first.
⇒ Function applications are reduced *before* their arguments.
- If no further redex is found, the expression is in **normal form** and reduction terminates.

(Reducing a function application $f\ e$: replace application by body of f in which the formal parameter is replaced by argument e .)

Lazy Evaluation

Example for normal order (\equiv outermost redex first) reduction:

```
fst :: (a,b) -> a
```

```
fst (x,y) = x
```

```
sqr :: Num a => a -> a
```

```
sqr x = x * x
```

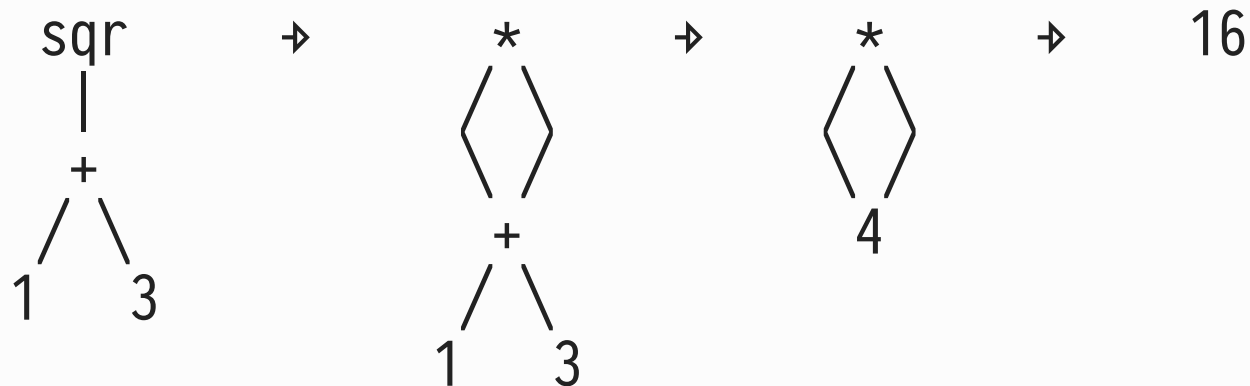
```
-- →: "reduces to"
```

fst (sqr (1 + 3), sqr 2)	→	sqr (1 + 3)	[fst]
	→	(1 + 3) * (1 + 3)	[sqr]
	→	4 * 4	[+ / +]
	→	16	[*]

Graph Reduction

Haskell avoids the duplication of work through **graph reduction**. Expressions are shared (referenced more than once) instead of duplicated.

Example (reduction of `sqr (1 + 3)`):



Graph Reduction and Sharing

Graph reduction and sharing ...

- ... makes normal order reduction never perform more reduction steps (\rightarrow) than applicative order reduction,
- ... can implement `let...in` efficiently,
- ... depends on the language semantics to be **free of side effects**:
 - sharing affects the number of evaluations of an expression,
 - (the number of) side effects are observable for an outsider.

Weak Head Normal Form (WHNF)

To save further evaluation (= reduction) effort, Haskell stops expression reduction once **weak head normal form** has been reached:

- Expression e is in **weak head normal form (WHNF)** if it is of the following forms:
 1. v (where v is an atomic value of type `Integer`, `Bool`, `Char`, ...),
 2. $c\ e_1\ e_2\ \dots\ e_n$ (where c an n -ary constructor function, like `(:)`),
 3. $f\ e_1\ e_2\ \dots\ e_m$ (where f is an n -ary function with $m < n$).
- **NB:** The arguments e_i need *not* be in WHNF for e to be in WHNF.

Weak Head Normal Form (WHNF)

- Haskell reduces values to WHNF only (\equiv stop criterion for reduction) unless we explicitly request reduction to normal form (e.g. when printing results).
- **Example:** Expressions in WHNF:

42	-- 1. atomic value
(sqr 2, sqr 4)	-- 2. tuple constructor (,)
f x : map f xs	-- 2. list constructor (:)
Just (40 + 2)	-- 2. Maybe constructor (Just)
(* (40 + 2))	-- 3. binary (*) applied to one argument only
(\x -> 40 + 2)	-- 3. lambda applied to no argument at all

Lazy Evaluation and Bottom (\perp)

- Haskell expressions may have the value **bottom** (\perp).
 - Examples: `error "..."`, `undefined`, `bomb` (see above).
- **Lazy evaluation** admits functions that return a non-bottom value even if they receive \perp as argument (these are the so-called **non-strict** functions):
 - A n -ary function f is **strict** in its i -th argument, if $f\ e_1 \dots e_{i-1} \perp e_{i+1} \dots e_n = \perp$.
- **Examples:**
 - `const :: a -> b -> a`: strict in first, non-strict in second argument
 - `&& :: Bool -> Bool -> Bool`: dito

Lazy Evaluation and Bottom (\perp)

⚠ If a function **pattern matches** on an argument, Haskell semantics define it to be **strict** in that argument.

- **Example:**

```
data T = T Int

f :: T -> Int
f (T x) = 42           -- x not needed to produce result

f undefined           →  $\perp$ 
f (T undefined) → 42  -- argument evaluated but only
                     -- until pattern match can be decided
```

- Note: Haskell supports *lazy pattern matching* via syntax `~<pat>`.

A Crazy (Yet Declarative) Implementation of List Minimum?

- To find the minimum in a non-empty list `xs :: Ord a => [a]`:
 1. sort `xs` in ascending order (here: use *insertion sort*, $O(n^2)$), then
 2. return the first element:

```
min :: Ord a => [a] -> a  
min xs = (head . isort) xs
```

- 💡 Lazy evaluation never needs `xs` sorted in its entirety. Hmm...
- ⚠️ The following depends on our use of *insertion sort* (`isort`) as the sorting algorithm.

A Crazy (Yet Declarative) Implementation of List Minimum?

Proposed implementations of `min` and `isort`:

```
min :: Ord a => [a] -> a
min = head . isort                                -- [min]

isort :: Ord a => [a] -> [a]
isort []      = []                                -- [isort.1]
isort (x:xs) = ins x (isort xs)                  -- [isort.2]
  where
    ins x []      = [x]                            -- [ins.1]
    ins x (y:ys) | x < y      = x:y:ys              -- [ins.2]
                  | otherwise = y:ins x ys          -- [ins.3]
```

- Label the branches of function definitions via `[f.n]` to refer to them during reduction.

A Crazy (Yet Declarative) Implementation of List Minimum?

Reduce `min [8,6,1,7,5]`, use stop criterion WHNF:

<code>min [8,6,1,7,5]</code>	
→ <code>(head . isort) [8,6,1,7,5]</code>	<code>[min]</code>
→ <code>head (isort [8,6,1,7,5])</code>	<code>[(.)]</code>
→ <code>head (ins 8 (ins 6 (ins 1 (ins 7 (ins 5 [])))))</code>	<code>[isort.2+]</code>
→ <code>head (ins 8 (ins 6 (ins 1 (ins 7 [5])))</code>	<code>[ins.1]</code>
→ <code>head (ins 8 (ins 6 (ins 1 (5 : ins 7 []))))</code>	<code>[ins.3]</code> *
→ <code>head (ins 8 (ins 6 (1 : (5 : ins 7 []))))</code>	<code>[ins.2]</code>
→ <code>head (ins 8 (1 : ins 6 (5 : ins 7 [])))</code>	<code>[ins.3]</code>
→ <code>head (1 : ins 8 (ins 6 (5 : ins 7 [])))</code>	<code>[ins.3]</code>
→ <code>1</code>	<code>[head]</code>

* `(5 : ins 7 [])` is in WHNF \Rightarrow do not reduce any further.

Observing Reduction in GHCi

- Command `:sprint <e>` in `ghci` reduces `<e>` to WHNF.
- **Example:** observe behavior of function `delete` of pre-packaged module `Data.List`:

```
Prelude> :doc delete
delete :: (Eq a) => a -> [a] -> [a]
base Data.List
delete x removes the first occurrence of x
from its list argument. For example,
```

```
delete 'a' "banana" == "bnana"
```

It is a special case of `deleteBy`, which allows the programmer to supply their own equality test.

Infinite Lists (and other Data Structures)

A welcome consequence of lazy evaluation: programs can handle **infinite lists** as long as any run will inspect only a finite prefix of such a list.

- Enables a **modular style of programming** in which
 1. *generator functions* produce an infinite number of solutions/approximations/...
 2. *test functions* select one (or a finite number of) solutions from this infinite stream.
- Modularity: can formulate generator and test functions **independently**.

Example: Newton-Raphson Square Root Approximation

- **Idea:** Iteratively approximate the square root of x :
 1. $a_0 = x / 2$
 2. $a_{i+1} = (a_i + x / a_i) / 2, i \geq 1$
- To compute this series of a_i , employ
 - **generator** `iterate :: (a -> a) -> a -> [a]`:
`iterate f x = [x, f x, f (f x), ...]`
 - **test** `within :: (Ord a, Num a) => a -> [a] -> a`:
`within ε xs` consumes `xs` until two adjacent elements differ less than `ε` (for the first time).

Example: Numerical Integration Through Interval Subdivision

- **Idea:** To compute $\int (f(x)) dx$ between x_1 and x_2 , keep subdividing the interval $[x_1, x_2]$ until it is reasonable to assume that f is linear in the interval. Build on additive property of integration:

$$\begin{aligned} \int_{x_1}^{x_2} (f(x)) dx &= \int_{x_1}^{x_1} (f(x)) dx + \int_{x_1}^{x_2} (f(x)) dx \\ &= \int_{x_1}^{x_1} (f(x)) dx + \int_{x_1}^{x_2} (f(x)) dx + \int_{x_2}^{x_2} (f(x)) dx + \int_{x_2}^{x_2} (f(x)) dx \end{aligned}$$