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## Reminder

Thesis

- The expressive power of a language, which supports modular design, depends much on the power of the concepts and primitives allowing to combine solutions of subproblems to the solution of the overall problem. (Keyword: *glue*). (Example: making of a chair)
- Functional programming provides two new, especially powerful means ("glues") for this purpose:
  1. *Higher order functions (functionals)*
  2. *Lazy evaluation*Modularization and re-use offer thus even *conceptually* (and not just technically (lexical scoping, separate compilation, etc.)) new opportunities and become much easier to apply
- Modularization (smaller, simpler, more general) is the guideline, which should be used by functional programmers for guidance

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## Reminder (Cont'd)

We did talk about...

- Higher-order functions as glue for *glueing functions together*

We did not yet talk about...

- Lazy evaluation as glue for *glueing programs together*

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## I Glueing Functions Together

See part I of this lecture.

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## II Glueing Programs Together

If  $f$  and  $g$  are programs, then also

$$g \cdot f$$

is a program. Applied to the input `input`, it yields the output

$$g (f \text{ input})$$

A possible conventional implementation (glue): communication via files

Possible problems of such an implementation:

- Temporary files are often too large
- $f$  might not terminate

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## Functional Glue

*Lazy evaluation* offers a more elegant remedy.

As a glue, it allows:

- Decomposition of a problem into a
  - *generator* and a
  - *selector*component.

*Intuition:*

- The generator component "runs as little as possible" until it is terminated by the selector component.

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## Example 1: Computing Square Roots

*Computing Square Roots (according to Newton-Raphson)*

Given:  $N$  Sought: `squareRoot(N)`

Iteration formula:

$$a(n+1) = (a(n) + N/a(n)) / 2$$

Justification: If converging to some limit  $a$ , we have:

$$a = (a + N/a) / 2$$

$$\Rightarrow 2a = a + N/a$$

$$a = N/a$$

$$a*a = N$$

$$a = \text{squareRoot}(N)$$

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## Compare this...

...with a typical imperative (Fortran-) program:

```
C    N is called ZN here so that it has the right type
      X = A0
      Y = A0 + 2.*EPS
C    The value of Y does not matter so long as ABS(X-Y).GT.EPS
100  IF (ABS(X-Y).LE.EPS) GOTO 200
      Y = X
      X = (X + ZN/X) / 2.
      GOTO 100
200  CONTINUE
C    The square root of ZN is now in X
```

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## The Functional Version 1(4)

Computing the next approximation

$$\text{next } N \ x = (x + N/x) / 2$$

Denoting this function  $f$ , we are interested in computing the sequence of approximations:

$$[a_0, f \ a_0, f(f \ a_0), f(f(f \ a_0)), \dots]$$

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## The Functional Version 2(4)

The function `repeat` computes this (possibly infinite) sequence of approximations. It is the *generator* component in this example:

```
repeat f a = cons a (repeat f (f a))
```

Applying `repeat` to the arguments `next N` and `a0` yields the desired sequence of approximations:

```
repeat (next N) a0
```

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## The Functional Version 3(4)

Note: The evaluation of

```
repeat (next N) a0
```

does not terminate!

Remedy: ...computing `squareroot N` up to a given tolerance `eps > 0`. Instrumental is: the *selector* component.

Implementation:

```
within eps (cons a (cons b rest))
  = b,                if abs(a-b) <= eps
  = within eps (cons b rest), otherwise
```

Still to do: Combining the components/modules:

```
sqrt a0 eps N = within eps (repeat (next N) a0)
```

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## The Functional Version 4(4)

Summing up:

- `repeat...` generator component:  
[`a0`, `f a0`, `f(f a0)`, `f(f(f a0))`, ...]  
...potentially infinite, no limit on the length
- `within...` selector component:  
`fi a0` with `abs(fi a0 - fi+1 a0) <= eps`  
...lazy evaluation ensures that the selector function is applied eventually  $\Rightarrow$  termination!

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## Evidence of Modularity: Variants

Consider another stop criterion:

- ...instead of awaiting the difference of successive approximations to approach zero (`<= eps`), await their ratio to approach one (`<= 1+eps`)

Implementation:

```
relative eps (cons a (cons b rest))
  = b,                if abs(a-b) <= eps * abs b
  = relative eps (cons b rest), otherwise
```

Still to do: (re-) composition of the components/modules:

```
relativesqrt a0 eps N = relative eps (repeat (next N) a0)
```

Note: The generator, i.e., the "module" computing the sequence of approximations can be reused unchanged.

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## Example 2: Numerical Integration

*Numerical Integration*

Given: A real valued function `f` of one real argument; two endpoints `a` und `b` of an interval

Sought: The area under `f` between `a` and `b`

Naive Implementation:

...supposed that the function `f` is roughly linear between `a` und `b`.

```
easyintegrate f a b = (f a + f b) * (b-a) / 2
```

...sufficiently precise at most for very small intervals.

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## Refinements 1(4)

Idea

- Halve the interval, compute the areas for both subintervals according to the previous formula, and add the two results
- Continue the previous step repeatedly

The function `integrate` implements this strategy:

```
integrate f a b = cons (easyintegrate f a b)
                  map addpair (zip (integrate f a mid)
                                   (integrate f mid b)))
  where mid = (a+b)/2
```

Reminder:

```
zip (cons a s) (cons b t) = cons (pair a b) (zip s t)
```

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## Refinements 2(4)

- `integrate` is sound but inefficient (redundant computations of `f a`, `f b`, and `f mid`)

The following version of `integrate` is free of this deficiency

```
integrate f a b = integ f a b (f a) (f b)
integ f a b fa fb = cons ((fa+fb)*(b-a)/2)
                       (map addpair (zip (integ f a m fa fm)
                                           (integ f m b fm fb)))
  where m = (a+b)/2
        fm = f m
```

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## Refinements 3(4)

Note: The evaluation of

```
integrate f a b
```

does not terminate!

Remedy: ...computing `integrate f a b` up to some limit `eps > 0`.

Implementation:

```
Variant A:  within eps (integrate f a b)
Variant B:  relative eps (integrate f a b)
```

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## Refinements 4(4)

Summing up...

- Generator component:  
`integrate`  
...potentially infinite, no limit on the length
- Selector component:  
`within, relative`  
...lazy evaluation ensures that the selector function is applied eventually  $\Rightarrow$  Terminierung!

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## Example 3: Numerical Differentiation

*Numerical Differentiation*

Given: A real valued function  $f$  of one real argument; a point  $x$

Sought: The slope of  $f$  at point  $x$

Naive Implementation:

...supposed that the function  $f$  between  $x$  and  $x+h$  does not "curve much"

$$\text{easydiff } f \ x \ h = (f(x+h) - f \ x) / h$$

...sufficiently precise at most for very small values of  $h$ .

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## Refinements 1(2)

Generate a sequence of approximations getting successively "better"

```
differentiate h0 f x = map (easydiff f x) (repeat halve h0)
halve x = x/2
```

Selecting a sufficiently precise approximation

```
within esp (differentiate h0 f x)
```

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## Conclusion 1(4)

The composition pattern, which in fact is common to all three examples becomes apparent again. It consists of

- generator (not limited itself!) and
- selector (ensuring termination thanks to lazy evaluation!)

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## Conclusion 2(4)

Thesis

- ...modularity is the key to *programming in the large*

Observation

- ...just modules do not suffice
- ...the benefit of decomposing a problem into modular sub-problems depends much on the capabilities for the combination of modules (glue!)
- ...the availability of proper glue is substantial!

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## Conclusion 3(4)

Fact

- Functional programming offers two new kinds of glue
  - *Higher-order functions*
  - *Lazy evaluation*
- Higher-order functions and lazy evaluation allow substantially new exciting modular decompositions of problems (by offering elegant composition means) as here given evidence by an array of impressive examples
- In essence, it is the superior glue, which makes functional programs to be written so concisely and elegantly

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## Conclusion 4(4)

Guideline

- Functional programmers should strive for adequate modularization and generalization
  - Especially, if a portion of a program looks ugly or appears to be too complex
- Functional programmers should expect that *higher-order functions* and *lazy evaluation* are the tools for doing this

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## Lazy vs. Eager Evaluation

Reconsidering...

- In view of the previous arguments...
  - The benefits of lazy evaluation as glue is so evident that lazy evaluation is too important to make it a *second-class citizen*.
  - Lazy evaluation is possibly the most powerful glue functional programming has to offer.
  - Access to such a powerful means should not frivolously be dropped.

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## Worthwhile too...

...the examination of the following papers:

- Paul Hudak. *Conception, Evolution, and Application of Functional Programming Languages*. ACM Computing Surveys, Vol. 21, No. 3, 359-411, 1989.
- Phil Wadler. *The Essence of Functional Programming*. In Conference Record of the 19th Annual Symposium on Principles of Programming Languages (POPL'92), 1-14, 1992.
- Simon Peyton Jones. *Wearing the Hair Shirt – A Retrospective on Haskell*. Invited Keynote Presentation at the 30th Annual Symposium on Principles of Programming Languages (POPL'03), 2003.  
Slides: <http://research.microsoft.com/Users/simonpj/papers/haskell-retrospective/index.html>

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## Last but not least...

Next lecture...

- Thu, April 26, 2007, lecture time: 4.15 p.m. to 5.45 p.m., lecture room on the ground floor of the building Argentinierstr. 8

Second assignment...

- Please check out the homepage of the course for details.