

Coursework 8 (Scala, Regular Expressions, Brainf***)

This coursework is worth 10%. It is about regular expressions, pattern matching and an interpreter. The first part is due on 30 November at 11pm; the second, more advanced part, is due on 21 December at 11pm. In the first part, you are asked to implement a regular expression matcher based on derivatives of regular expressions. The reason is that regular expression matching in Java can sometimes be extremely slow. The advanced part is about an interpreter for a very simple programming language.

Important:

- Make sure the files you submit can be processed by just calling `scala <<filename.scala>>` on the commandline. Use the template files provided and do not make any changes to arguments of functions or to any types. You are free to implement any auxiliary function you might need.
- Do not use any mutable data structures in your submissions! They are not needed. This means you cannot create new `Arrays` or `ListBuffers`, for example.
- Do not use `return` in your code! It has a different meaning in Scala, than in Java.
- Do not use `var`! This declares a mutable variable. Only use `val`!
- Do not use any parallel collections! No `.par` therefore! Our testing and marking infrastructure is not set up for it.

Also note that the running time of each part will be restricted to a maximum of 360 seconds on my laptop

Disclaimer

It should be understood that the work you submit represents your own effort! You have not copied from anyone else. An exception is the Scala code I showed during the lectures or uploaded to KEATS, which you can freely use.

Part 1 (6 Marks)

The task is to implement a regular expression matcher that is based on derivatives of regular expressions. Most of the functions are defined by recursion over regular expressions and can be elegantly implemented using Scala's pattern-matching. The implementation should deal with the following regular expressions, which have been predefined in the file `re.scala`:

$r ::=$	0	cannot match anything
	1	can only match the empty string
	c	can match a character (in this case c)
	$r_1 + r_2$	can match a string either with r_1 or with r_2
	$r_1 \cdot r_2$	can match the first part of a string with r_1 and then the second part with r_2
	r^*	can match zero or more times r

Why? Knowing how to match regular expressions and strings will let you solve a lot of problems that vex other humans. Regular expressions are one of the fastest and simplest ways to match patterns in text, and are endlessly useful for searching, editing and analysing data in all sorts of places (for example analysing network traffic in order to detect security breaches). However, you need to be fast, otherwise you will stumble over problems such as recently reported at

- <http://stackstatus.net/post/147710624694/outage-postmortem-july-20-2016>
- <https://vimeo.com/112065252>
- <http://davidvgalbraith.com/how-i-fixed-atom/>

Tasks (file `re.scala`)

- (1a) Implement a function, called *nullable*, by recursion over regular expressions. This function tests whether a regular expression can match the empty string. This means given a regular expression it either returns true or false.

$nullable(\mathbf{0})$	$\stackrel{\text{def}}{=} false$
$nullable(\mathbf{1})$	$\stackrel{\text{def}}{=} true$
$nullable(c)$	$\stackrel{\text{def}}{=} false$
$nullable(r_1 + r_2)$	$\stackrel{\text{def}}{=} nullable(r_1) \vee nullable(r_2)$
$nullable(r_1 \cdot r_2)$	$\stackrel{\text{def}}{=} nullable(r_1) \wedge nullable(r_2)$
$nullable(r^*)$	$\stackrel{\text{def}}{=} true$

[1 Mark]

- (1b) Implement a function, called *der*, by recursion over regular expressions. It takes a character and a regular expression as arguments and calculates the derivative regular expression according to the rules:

$$\begin{aligned}
\text{der } c \text{ (}\mathbf{0}\text{)} &\stackrel{\text{def}}{=} \mathbf{0} \\
\text{der } c \text{ (}\mathbf{1}\text{)} &\stackrel{\text{def}}{=} \mathbf{0} \\
\text{der } c \text{ (}d\text{)} &\stackrel{\text{def}}{=} \text{if } c = d \text{ then } \mathbf{1} \text{ else } \mathbf{0} \\
\text{der } c \text{ (}r_1 + r_2\text{)} &\stackrel{\text{def}}{=} (\text{der } c \text{ } r_1) + (\text{der } c \text{ } r_2) \\
\text{der } c \text{ (}r_1 \cdot r_2\text{)} &\stackrel{\text{def}}{=} \text{if nullable}(r_1) \\
&\quad \text{then } ((\text{der } c \text{ } r_1) \cdot r_2) + (\text{der } c \text{ } r_2) \\
&\quad \text{else } (\text{der } c \text{ } r_1) \cdot r_2 \\
\text{der } c \text{ (}r^*\text{)} &\stackrel{\text{def}}{=} (\text{der } c \text{ } r) \cdot (r^*)
\end{aligned}$$

For example given the regular expression $r = (a \cdot b) \cdot c$, the derivatives w.r.t. the characters a , b and c are

$$\begin{aligned}
\text{der } a \text{ } r &= (\mathbf{1} \cdot b) \cdot c \quad (= r') \\
\text{der } b \text{ } r &= (\mathbf{0} \cdot b) \cdot c \\
\text{der } c \text{ } r &= (\mathbf{0} \cdot b) \cdot c
\end{aligned}$$

Let r' stand for the first derivative, then taking the derivatives of r' w.r.t. the characters a , b and c gives

$$\begin{aligned}
\text{der } a \text{ } r' &= ((\mathbf{0} \cdot b) + \mathbf{0}) \cdot c \\
\text{der } b \text{ } r' &= ((\mathbf{0} \cdot b) + \mathbf{1}) \cdot c \quad (= r'') \\
\text{der } c \text{ } r' &= ((\mathbf{0} \cdot b) + \mathbf{0}) \cdot c
\end{aligned}$$

One more example: Let r'' stand for the second derivative above, then taking the derivatives of r'' w.r.t. the characters a , b and c gives

$$\begin{aligned}
\text{der } a \text{ } r'' &= ((\mathbf{0} \cdot b) + \mathbf{0}) \cdot c + \mathbf{0} \\
\text{der } b \text{ } r'' &= ((\mathbf{0} \cdot b) + \mathbf{0}) \cdot c + \mathbf{0} \\
\text{der } c \text{ } r'' &= ((\mathbf{0} \cdot b) + \mathbf{0}) \cdot c + \mathbf{1} \quad (\text{is nullable})
\end{aligned}$$

Note, the last derivative can match the empty string, that is it is *nullable*.

[1 Mark]

- (1c) Implement the function *simp*, which recursively traverses a regular expression from the inside to the outside, and on the way simplifies every regular expression on the left (see below) to the regular expression on the right, except it does not simplify inside *-regular expressions.

$$\begin{aligned}
r \cdot \mathbf{0} &\mapsto \mathbf{0} \\
\mathbf{0} \cdot r &\mapsto \mathbf{0} \\
r \cdot \mathbf{1} &\mapsto r \\
\mathbf{1} \cdot r &\mapsto r \\
r + \mathbf{0} &\mapsto r \\
\mathbf{0} + r &\mapsto r \\
r + r &\mapsto r
\end{aligned}$$

For example the regular expression

$$(r_1 + \mathbf{0}) \cdot \mathbf{1} + ((\mathbf{1} + r_2) + r_3) \cdot (r_4 \cdot \mathbf{0})$$

simplifies to just r_1 . **Hint:** Regular expressions can be seen as trees and there are several methods for traversing trees. One of them corresponds to the inside-out traversal, which is sometimes also called post-order traversal. Furthermore, remember numerical expressions from school times: there you had expressions like $u + \dots + (1 \cdot x) - \dots (z + (y \cdot 0)) \dots$ and simplification rules that looked very similar to rules above. You would simplify such numerical expressions by replacing for example the $y \cdot 0$ by 0, or $1 \cdot x$ by x , and then look whether more rules are applicable. If you organise the simplification in an inside-out fashion, it is always clear which rule should be applied next. [2 Marks]

- (1d) Implement two functions: The first, called *ders*, takes a list of characters and a regular expression as arguments, and builds the derivative w.r.t. the list as follows:

$$\begin{aligned} \text{ders } (\text{Nil}) \ r &\stackrel{\text{def}}{=} \ r \\ \text{ders } (c :: cs) \ r &\stackrel{\text{def}}{=} \ \text{ders } cs \ (\text{simp}(\text{der } c \ r)) \end{aligned}$$

Note that this function is different from *der*, which only takes a single character.

The second function, called *matcher*, takes a string and a regular expression as arguments. It builds first the derivatives according to *ders* and after that tests whether the resulting derivative regular expression can match the empty string (using *nullable*). For example the *matcher* will produce true for the regular expression $(a \cdot b) \cdot c$ and the string *abc*, but false if you give it the string *ab*. [1 Mark]

- (1e) Implement a function, called *size*, by recursion over regular expressions. If a regular expression is seen as a tree, then *size* should return the number of nodes in such a tree. Therefore this function is defined as follows:

$$\begin{aligned} \text{size}(\mathbf{0}) &\stackrel{\text{def}}{=} \ 1 \\ \text{size}(\mathbf{1}) &\stackrel{\text{def}}{=} \ 1 \\ \text{size}(c) &\stackrel{\text{def}}{=} \ 1 \\ \text{size}(r_1 + r_2) &\stackrel{\text{def}}{=} \ 1 + \text{size}(r_1) + \text{size}(r_2) \\ \text{size}(r_1 \cdot r_2) &\stackrel{\text{def}}{=} \ 1 + \text{size}(r_1) + \text{size}(r_2) \\ \text{size}(r^*) &\stackrel{\text{def}}{=} \ 1 + \text{size}(r) \end{aligned}$$

You can use *size* in order to test how much the ‘evil’ regular expression $(a^*)^* \cdot b$ grows when taking successive derivatives according the letter *a* without simplification and then compare it to taking the derivative, but simplify the result. The sizes are given in `re.scala`. [1 Mark]

Background

Although easily implementable in Scala, the idea behind the derivative function might not so easy to be seen. To understand its purpose better, assume a regular expression r can match strings of the form $c::cs$ (that means strings which start with a character c and have some rest, or tail, cs). If you take the derivative of r with respect to the character c , then you obtain a regular expression that can match all the strings cs . In other words, the regular expression $der\ c\ r$ can match the same strings $c::cs$ that can be matched by r , except that the c is chopped off.

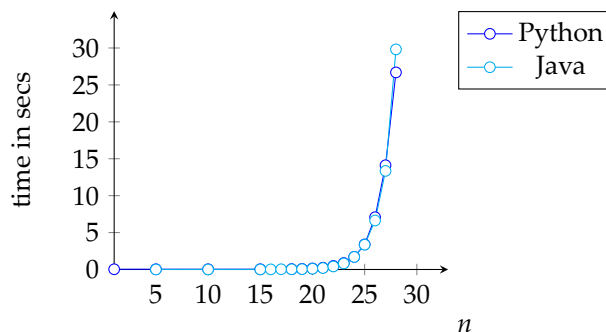
Assume now r can match the string abc . If you take the derivative according to a then you obtain a regular expression that can match bc (it is abc where the a has been chopped off). If you now build the derivative $der\ b\ (der\ a\ r)$ you obtain a regular expression that can match the string c (it is bc where b is chopped off). If you finally build the derivative of this according c , that is $der\ c\ (der\ b\ (der\ a\ r))$, you obtain a regular expression that can match the empty string. You can test whether this is indeed the case using the function `nullable`, which is what your matcher is doing.

The purpose of the `simp` function is to keep the regular expression small. Normally the derivative function makes the regular expression bigger (see the SEQ case and the example in (1b)) and the algorithm would be slower and slower over time. The `simp` function counters this increase in size and the result is that the algorithm is fast throughout. By the way, this algorithm is by Janusz Brzozowski who came up with the idea of derivatives in 1964 in his PhD thesis.

[https://en.wikipedia.org/wiki/Janusz_Brzozowski_\(computer_scientist\)](https://en.wikipedia.org/wiki/Janusz_Brzozowski_(computer_scientist))

If you want to see how badly the regular expression matchers do in Java and Python with the 'evil' regular expression, then have a look at the graphs below (you can try it out for yourself: have a look at the file `catastrophic.java` on KEATS). Compare this with the matcher you have implemented. How long can the string of a 's be in your matcher and stay within the 30 seconds time limit?

Graph: $(a^*)^* \cdot b$ and strings $\underbrace{a \dots a}_n$



Part 2 (4 Marks)

Coming from Java or C++, you might think Scala is a quite esoteric programming language. But remember, some serious companies have built their business on Scala. And there are far more esoteric languages out there. One is called *brainf****. Urban Müller developed this language in 1993. A close relative was already introduced in ... by Corrado Böhm, an Italian computer pioneer, who unfortunately died a few months ago. One feature of *brainf**** is its minimalistic set of instructions. It has just 8 instructions, all of which are single characters. Despite this minimalism, this language, given enough memory, has been shown to be Turing complete. In this part you will implement an interpreter for this language.

Tasks (file `bf.scala`)

(2a)

(2b)

(2c)