Learn Physics with Functional Programming

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Chapter 4: Exercises

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4.2 For $f(x) = x^3$, we have $f'(x) = 3x^2$, so that the relative error is defined by

$$\begin{aligned}
\mathrm{err}(x,a) &= \left| \frac{\frac{f(x+a/2)-f(x-a/2)}{a} - f'(x)}{f'(x)} \right| \\
&= \left| \frac{\frac{(x+a/2)^3-(x-a/2)^3}{a} - 3x^2}{3x^2} \right| \\
&= \left| \frac{\frac{\begin{array}{l}[x^3 + (3x^2a)/2 + (3xa^2)/4 + a^3/8] \\ \quad - [x^3 - (3x^2a)/2 + (3xa^2)/4 - a^3/8]\end{array}}{a} - 3x^2}{3x^2} \right| \\
&= \left| \frac{\frac{3x^2a + a^3/4 - 3x^2a}{a}}{3x^2} \right| \\
&= \left| \frac{\frac{a^2}{4}}{3x^2} \right| \\
&= \left| \frac{a^2}{12x^2} \right| \\
&= \frac{a^2}{12x^2},
\end{aligned}$$

since $a^2 \geq 0$ and $x^2 \geq 0$.

Thus we have an error of 1 percent if

$$\begin{aligned}\operatorname{err}(x,a) &= 0.01\\ \Leftrightarrow \frac{a^2}{12x^2} &= 0.01\\ \Leftrightarrow a^2 &= 0.12x^2\\ \Leftrightarrow a &= |x|\sqrt{0.12}\end{aligned}$$

Then, for $x = 4$, we have

$$\begin{aligned}a &= 4\sqrt{0.12}\\ &\approx 1.3856406460551018\end{aligned}$$

and for $x = 0.1$, we have

$$\begin{aligned}a &= 0.1\sqrt{0.12}\\ &\approx 3.4641016151377546 \times 10^{-2}.\end{aligned}$$

4.3 Suppose we have a function f and independent variable, say x, such that `derivative 0.01 f x` produces at least a 10 percent error, $\operatorname{err}(x, \epsilon)$, compared to the exact derivative, $f'(x)$. Then, we have

$$\begin{aligned}\operatorname{err}(x,\epsilon) &= \operatorname{err}(x, 0.01)\\ &= \left|\frac{\frac{f(x+\epsilon/2)-f(x-\epsilon/2)}{\epsilon} - f'(x)}{f'(x)}\right|\\ &= \left|\frac{\frac{f(x+0.01/2)-f(x-0.01/2)}{0.01} - f'(x)}{f'(x)}\right|\\ &= \left|\frac{\frac{f(x+0.005)-f(x-0.005)}{0.01} - f'(x)}{f'(x)}\right|\\ &\geq 0.1.\end{aligned}$$

If we substitute $\epsilon = 0.01$, $x = \pi \approx 3.141592653589793$, and $f(x) = \cos x$ into the above, we have $f'(x) = -\sin x$, so that

$$\begin{aligned}\operatorname{err}(x,\epsilon) &= \operatorname{err}(\pi, 0.01)\\ &= \left|\frac{\frac{\cos(\pi+0.005)-\cos(\pi-0.005)}{0.01} + \sin\pi}{-\sin\pi}\right|\\ &\approx 1.0\\ &\geq 0.1.\end{aligned}$$

4.4 We cannot apply our error function in 4.3 to `derivative a cos`, since it results in division by 0, but at values close to `t = 0`, we see an initial increase in the error as we move from small values of `a` which stop increasing as we increase `a` by multiples of 10 past `a = 10`.

For the following definition of the error function

```
err :: (R -> R) -> (R -> R) -> R -> R -> R
err f df t a = abs ((derivative a f t - df t) / df t)
```

we have the following output from `ghci`:

```
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 0.01
4.166661374023121e-6
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 0.1
4.166145864253412e-4
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 1
4.114892279159413e-2
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 10
1.191784854932627
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 100
1.0052474970740786
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 1000
1.000935543610645
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 10000
1.000197593287754
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 100000
1.0000199968037815
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 1000000
0.999999644337597
ghci> err (\x -> cos x) (\x -> -sin x) 0.1 10000000
1.000000195308493
```