

# Project 1

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## **Abstract**

## Introduction

Computing has had and still have an undeniable influence on science. has allowed scientist to explore everything from the tiniest scale of an atom, to tropical cyclones and galaxies. Therefore understanding the inner workings behind a computer program is critical in order to avoid unwanted errors. Errors which in the worst case can have catastrophic consequences [1].

Our aim is to investigate some of the common errors one might face if one doesn't think when developing code. To begin with we will look at a how to solve a second order differential equation, specifically the general one dimensional Poisson's equation (10).

$$f(x) = -\frac{\partial^2 u}{\partial x^2} \quad (1)$$

## Numerical differentiation

Computers operate in discrete steps, which means that variables are stored as discrete variables. A discrete variable defined over a particular range would have step length  $h$  between each value and can not represent any values in between. This means that how well a discrete variable would represent the continuous variable depends on the size of the step length. The step length  $h$  can either be set manually or it can be determined based on the start and end point of our particular range,  $h = \frac{x_n - x_0}{n}$ . Where  $n$  is the number of points we choose to have in our range. The shorter the step length in the discrete variable the better it will approximate the continuous variable.

The simplest way to compute the derivate numerically is to use what is called forward difference method eq.(10) or equivalently backward difference method (eq.11). If we include the limit as  $\lim_{h \rightarrow 0}$  we obtain the classic definition of the derivate.

$$f'(x) \approx \frac{f(x+h) - f(x)}{h} \quad (2)$$

$$f'(x) \approx \frac{f(x-h) - f(x)}{-h} \quad (3)$$

Since numerical differentiation always will give an approximation of the derivate, we would like to quantify our error. The error can be derived if we do a taylor series expansion of the  $f(x+h)$  term in around  $x$ .

$$f(x+h) = f(x) + h'f(x) + \frac{h^2 f''(x)}{2} + \frac{h^3 f'''(x)}{6} + \dots \quad (4)$$

If we next insert this Taylor expansion into eq.(12) we get:

$$f'(x) = f'(x) + \frac{hf''(x)}{2} + \frac{h^2f'''(x)}{6} + \dots \quad (5)$$

Our approximation of the derivate includes  $f'(x)$  and some terms which are proportional to  $h, h^2, h^3 \dots$  and since  $h$  is assumed to be small the  $h$  terms would dominate. The error is said to be of the order  $h$ .

To get a numerical scheme for the second derivate we would just take the derivate of eq. (10) except for a slight modification. Instead of looking at  $f''(x) \approx \frac{f'(x+h)-f'(x)}{h}$  we would use  $f''(x) \approx \frac{f'(x)-f'(x-h)}{h}$ , which are equivalent to each other see. [2].

$$f''(x) \approx \frac{f(x+h) - f(x) - f(x-h) + f(x-h)}{h^2} \quad (6)$$

Then after a bit of a clean up we get an approximation for the second order derivate (eq. (15)).

$$f''(x) \approx \frac{f(x+h) - 2f(x) + f(x-h)}{h^2} \quad (7)$$

Then to quantify the error we proceed as for the first order derivate, by expanding  $f(x+h)$  and  $f(x-h)$ .

$$f(x-h) = f(x) - hf'(x) + \frac{h^2f''(x)}{2} - \frac{h^3f'''(x)}{6} \dots \quad (8)$$

Next we substitute the two Taylor expansion eq. (8) and eq. (12) into the expression for second order derivate eq. (15).

$$f''(x) \approx f''(x) + \frac{h^2f^{(4)}(x)}{4!} + \frac{h^4f^{(6)}(x)}{6!} + \dots \quad (9)$$

Then we see that leading error term is for the second derivate is  $\mathcal{O}(h^2)$ . ««««< HEAD

## Method

### Numerical differentiation

Computers operate in discrete steps, which means that variables are stored as discrete variables. A discrete variable defined over a particular range would

have step length  $h$  between each value and can not represent any values in between. This means that how well a discrete variable would represent the continuous variable depends on the size of the step length. The step length  $h$  can either be set manually or it can be determined based on the start and end point of our particular range,  $h = \frac{x_n - x_0}{n}$ . Where  $n$  is the number of points we choose to have in our range. The shorter the step length in the discrete variable the better it will approximate the continuous variable.

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$$f'(x) \approx \frac{f(x-h) - f(x)}{-h} \quad (11)$$

Since numerical differentiation always will give an approximation of the derivate, we would like to quantify our error. The error can be derived if we do a taylor series expansion of the  $f(x+h)$  term in around  $x$ .

$$f(x+h) = f(x) + h'f(x) + \frac{h^2 f''(x)}{2} + \frac{h^3 f'''(x)}{6} + \dots \quad (12)$$

If we next insert this taylor expansion into eq.(12) we get:

$$f'(x) = f'(x) + \frac{h f''(x)}{2} + \frac{h^2 f'''(x)}{6} + \dots \quad (13)$$

Our approximation of the derivate includes  $f'(x)$  and some terms which are proportional to  $h, h^2, h^3 \dots$  and since  $h$  is assumed to be small the  $h$  terms would dominate. The error is said to be of the order  $h$ .

To get a numerical scheme for the second derivate we would just take the derivate of eq. (10) except for a slight modification. Instead of looking at  $f''(x) \approx \frac{f'(x+h) - f'(x)}{h}$  we would use  $f''(x) \approx \frac{f'(x) - f'(x-h)}{h}$ , which are equivalent to each other see. [2].

$$f''(x) \approx \frac{f(x+h) - f(x) - f(x-h) + f(x-h)}{h^2} \quad (14)$$

Then after a bit of a clean up we get an approximation for the second order derivate (eq. (15)).

$$f''(x) \approx \frac{f(x+h) - 2f(x) + f(x-h)}{h^2} \quad (15)$$

Then to quantify the error we do a taylor expansion of  $f(x + h)$  and  $f(x - h)$   
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## Methods

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## Results

The thomas algorithm run time table 1 is roughly linear with the matrix size.

n	run time (s)
10	5.79e-05
100	2.91e-04
1000	1.71e-03
10000	1.97e-02
100000	1.55e-01
1000000	1.73e+00

Table 1: Run times of thomas algorithm for selected matrix sizes.

The improved thomas algorithm table 2 run time is in the same order of magnitude.

n	run time (s)
10	7.10e-05
100	1.41e-04
1000	1.46e-03
10000	1.45e-02
100000	1.04e-01
1000000	1.07e+00

Table 2: Run times of improved thomas algorithm when considering a töeplitz matrix.

Comparing the run times using LU decomposing and backward substituting (table 4) with run times using the thomas algorithm (table 1) we see that the thomas algorithm is roughly n times faster.

$\log_{10}(h)$	max(relative error)
-1.04	0.03
-2.00	-0.15
-3.00	-0.02
-4.00	-0.00
-5.00	-0.00
-6.00	-0.00

Table 3: Maximum relative error between analytic and numeric solution.

n	run time (s)
10	4.86e-04
100	8.52e-02
1000	7.49e+01

Table 4: Run time for solving  $A\mathbf{x} = \mathbf{b}$  by LU decomposing and backward substituting.

## References

1. Arnold, D. N. *The sinking of the Sleipner A offshore platform* <http://www-users.math.umn.edu/~arnold//disasters/sleipner.html>. (accessed: 01.09.2019).
2. Scott, B. M. *Second derivative formula derivation* <https://math.stackexchange.com/q/210269>. (accessed: 05.09.2019).