$$f(x_0+h) = f(x_0) + hf'(x_0) + \frac{h^2}{2}f''(x_0) + \frac{h^3}{6}f'''(x_0) + O(h^4)$$

Central difference formula

- We note the Taylor series should give us:

$$f(x_0-h) = f(x_0) - hf'(x_0) + \frac{h^2}{2}f''(x_0) - \frac{h^3}{6}f'''(x_0) + \mathcal{O}(h^4). \qquad (6)$$

$$\frac{f(x_0+h) - f(x_0-h)}{2h} = \frac{2hf'(x_0)}{2h} + 0 + \frac{2\frac{h^3}{6}f'''(x_0)}{2h} + \frac{O(h^4)}{2h}$$

- Then we have

$$D_0 f(x_0) \equiv \frac{1}{2}(D_h^+ f(x_0) + D_h^- f(x_0)) = \boxed{\frac{f(x_0+h) - f(x_0-h)}{2h}} \approx f'(x_0) + \frac{h^2}{6}K$$

CTD. F.D. B.D.

- This central difference *stencil* is second order accurate.

x_0-h x_0 x_0+h

Example: A second-order one sided finite difference formula for derivative:

$$\boxed{f'(x_0)} = \frac{-3f(x_0) + 4f(x_0+h) - f(x_0+2h)}{2h} + \frac{h^2}{3}f'''(\xi), \qquad (7)$$

$$= \frac{-3}{2h}f(x_0) + \frac{4}{2}\frac{1}{h}f(x_0+h) - \frac{1}{2h}f(x_0+2h)$$

x_0 x_0+h x_0+2h

where $\xi \in [x_0, x_0+h]$. How do we derive (7)? We want to set

undetermined coefficient

$$\boxed{D_2 f(x_0)} \equiv af(x_0) + bf(x_0+h) + cf(x_0+2h) = f'(x_0) + \mathcal{O}(h^2). \qquad (8)$$

and note

$$c\left(f(x_0+2h) = f(x_0) + \frac{2h}{1}f'(x_0) + \frac{(2h)^2}{2}f''(x_0) + \frac{(2h)^3}{6}f'''(x_0) + \mathcal{O}(h^4)\right) \qquad (9)$$

$$b\left(f(x_0+h) = f(x_0) + hf'(x_0) + \frac{h^2}{2}f''(x_0) + \frac{h^3}{6}f'''(x_0) + O(h^4)\right)$$

$$a\left(f(x_0) = f(x_0)\right)$$

$$af(x_0) + bf(x_0+h) + cf(x_0+2h) = (a+b+c)f(x_0) + (0 + bh + c(2h))f'(x_0)$$

$+\left(0 + b\frac{h^2}{2} + c\frac{(2h)^2}{2}\right) f''(x_0)$

So we need $bh + 2ch = 1$ $\quad a+b+c = 0$ $\quad b\frac{h^2}{2} + c\,2h^2 = 0$

So (8) is indeed

$af(x_0) + bf(x_0+h) + cf(x_0+2h) = D_h f(x_0)$

$$\cancel{D_h f(x_0)} = \underbrace{(a+b+c)}_{=0} f(x_0) + \underbrace{(b+2c)}_{=1}\frac{h}{1} f'(x_0) + \underbrace{(b+4c)}_{=0}\frac{h^2}{2} f''(x_0) + (b+8c)\frac{h^3}{6} f'''(x_0) + \mathcal{O}(h^4).$$

Now we can see this leads to

$$a + b + c = 0, \quad b + 2c = 1/h, \quad b + 4c = 0,$$

which gives $a = \frac{-3}{2h}$, $b = \frac{4}{2h}$, and $c = -\frac{1}{2h}$.

This method could be used to derive other finite difference formulas.

Example: A fourth-order central difference formula for derivative $f'(x_0)$:

$$f'(x_0) = \frac{-f(x_0+2h) + 8f(x_0+h) - 8f(x_0-h) + f(x_0-2h)}{12h} + \frac{h^4}{30} f^{(5)}(\xi),$$

where $\xi \in [x_0, x_0+h]$.

Note: We can get higher order approximations by adding more neighboring points.

Centered formula for the second derivative: We note, the difference formula for the second derivative could be drived as $D_h^+(D_h^- f(x_0)) = \frac{1}{h}(D_h^- f(x_0+h) - D_h^- f(x_0))$,

$$f''(x_0) \approx D^2 f(x_0) = D_h^+ D_h^- f(x_0) = \frac{\frac{f(x_0+h)-f(x_0)}{h} - \frac{f(x_0)-f(x_0-h)}{h}}{h}$$

$$= \frac{f(x_0-h) - 2f(x_0) + f(x_0+h)}{h^2}$$

$a f(x_0-h) + b f(x_0) + c f(x_0+h)$

$= a\,(f(x_0) - f'(x_0)h + \cdots$

$+\, b f(x_0)$

$+c\,(f(x_0) + f'(x_0)h) + \cdots \quad)$

And we can see that

$$f''(x_0) = \frac{f(x_0-h) - 2f(x_0) + f(x_0+h)}{h^2} - \boxed{\frac{h^2}{12} f^{(4)}(\xi)} \quad + O(h^4) \tag{10}$$

where $x_0 - h \le \xi \le x_0 + h$.

- (10) comes from adding the expressions for forward and backward difference formulas:

c $\quad f(x_0+h) = f(x_0) + hf'(x_0) + \frac{h^2}{2} f''(x_0) + \frac{h^3}{6} f'''(x_0) + \frac{h^4}{24} f^{(4)}(\xi_1)$

b $\quad f(x_0) = f(x_0)$

a $\quad f(x_0-h) = f(x_0) - hf'(x_0) + \frac{h^2}{2} f''(x_0) - \frac{h^3}{6} f'''(x_0) + \frac{h^4}{24} f^{(4)}(\xi_2)$

$$f(x_0+h) + f(x_0-h) = 2f(x_0) + h^2 f''(x_0) + \frac{h^4}{24}\left(f^{(4)}(\xi_1) + f^{(4)}(\xi_2)\right).$$

Richardson Extrapolation

- This is a method for generating higher order numerical methods using lower order ones.

Example 2: if we have a 2nd order accurate method for approximating the second derivative

- Central differences for second derivative $f''(x_0)$:

$4 \cdot D_h^2 f(x_0)$

$$\underbrace{f''(x_0)}_{=\,D_h^2 f(x_0)} = \frac{f(x_0-h)-2f(x_0)+f(x_0+h)}{h^2} = D^2 f(x_0) = D^+ D^- f(x_0)$$

Formula 1

$$-\boxed{\frac{h^2}{12}f^{(4)}(x_0)} - \frac{h^4}{360}f^{(6)}(x_0) + \mathcal{O}(h^5)$$

- If we use points one step further to the left and right, to expand in terms of $f(x_0 \pm 2h)$ (replace h by $2h$ in the formula above), we get;

Formula 2

$1 \cdot D_{2h}^2 f(x_0) =$

$$f''(x_0) = \frac{f(x_0-2h)-2f(x_0)+f(x_0+2h)}{(2h)^2}$$

$$-\frac{(2h)^2}{12}f^{(4)}(x_0) - \frac{(2h)^4}{360}f^{(6)}(x_0) + \mathcal{O}(h^5)$$

$$\frac{4 \cdot D_h^2 f(x_0) - D_{2h}^2 f(x_0)}{3}$$

$$= \frac{3f''(x_0)}{3} = \cancel{4\frac{h^2}{12}f^{(4)}(x_0) - \frac{4h^2}{12}f^{(4)}(x_0)}$$

$$-\frac{4h^4}{360}f^{(6)}(x_0) + \frac{16h^4}{360}f^{(6)}(x_0) + O(h^5)$$

$$= \frac{\frac{12h^4}{360}f^{(6)}(x_0)}{3} + O(h^5)$$

$$\frac{4D_h^2 f(x_0) - D_{2h}^2 f(x_0)}{3} = f''(x_0) = \frac{1}{30}h^4 f^{(6)}(x_0) + O(h^5)$$

new FD approx

- Combine the two formulas to eliminate the leading error term $\mathcal{O}(h^2)$:

$4D_h^2 f(x_0) - D_{2h}^2 f(x_0)$ "

$$\begin{aligned}
3f''(x_0) &= 4\left(\frac{f(x_0-h)-2f(x_0)+f(x_0+h)}{h^2}\right) \\
&-\left(\frac{f(x_0-2h)-2f(x_0)+f(x_0+2h)}{4h^2}\right) \\
&-4\left(\frac{h^2}{12}f^{(4)}(x_0)-\frac{h^4}{360}f^{(6)}(x_0)\right) \\
&+\frac{4h^2}{12}f^{(4)}(x_0)+\frac{16h^4}{360}f^{(6)}(x_0)+\mathcal{O}(h^5)
\end{aligned}$$

We use $D^2 f(x_0)$ twice !!

$$\begin{aligned}
3f''(x_0) &= 4\left(\frac{f(x_0-h)-2f(x_0)+f(x_0+h)}{h^2}\right) \\
&-\left(\frac{f(x_0-2h)-2f(x_0)+f(x_0+2h)}{4h^2}\right) \\
&+\frac{4h^4}{360}f^{(6)}(x_0)+\frac{16h^4}{360}f^{(6)}(x_0)+\mathcal{O}(h^5)
\end{aligned}$$

$$\begin{aligned}
3f''(x_0) &= 4\left(\frac{f(x_0-h)-2f(x_0)+f(x_0+h)}{h^2}\right) \\
&-\left(\frac{f(x_0-2h)-2f(x_0)+f(x_0+2h)}{4h^2}\right) \\
&+\frac{h^4}{30}f^{(6)}(x_0)+\mathcal{O}(h^5)
\end{aligned}$$

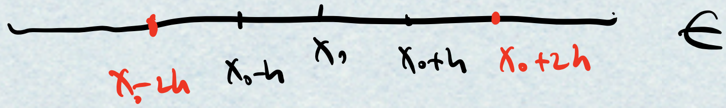
- Finally

$= D_h^2 f(x_0)$

$$\begin{aligned}
f''(x_0) &= \frac{4}{3}\left(\frac{f(x_0-h)-2f(x_0)+f(x_0+h)}{h^2}\right) \\
&-\frac{1}{3}\left(\frac{f(x_0-2h)-2f(x_0)+f(x_0+2h)}{4h^2}\right)+\frac{h^4}{90}f^{(6)}(\xi),
\end{aligned}$$

$= D_{2h}^2 f(x_0)$

where $\xi \in [x_0-2h, x_0+2h]$.



- Common denominator

$$f''(x_0) = \frac{-f(x_0-2h)+16f(x_0-h)-30f(x_0)+16f(x_0+h)-f(x_0+2h)}{12h^2} + \frac{h^4}{90}f^{(6)}(\xi).$$

- Fourth order accuracy!

Disadvantages

- Requires a wider stencil, i.e. more points, $f(x_0)$, $f(x_0+h)$, $f(x_0-h)$, $f(x_0+2h)$, and $f(x_0-2h)$.

- f needs to have nice, bounded higher order derivatives.

Roundoff and data errors

Example: Consider the centered difference approximation of $f'(0)$ for $f(x) = e^x$, at $x_0 = 0$

given h

C.T.D $\quad e^{x_0+h} \quad e^{x_0-h}$

$$f'(x_0) = \frac{f(x_0+h)-f(x_0-h)}{2h} = \frac{e^h-e^{-h}}{2h}$$

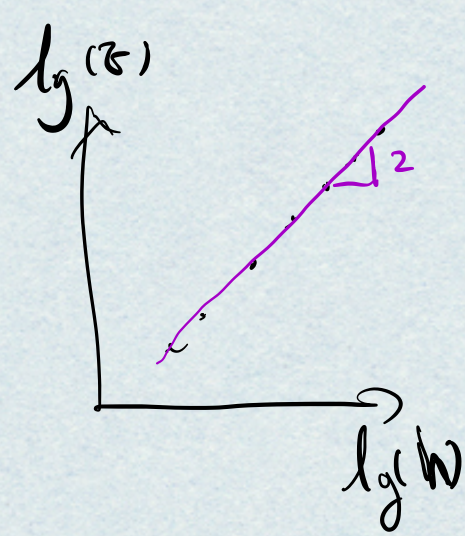
2nd order $= O(h^2)$

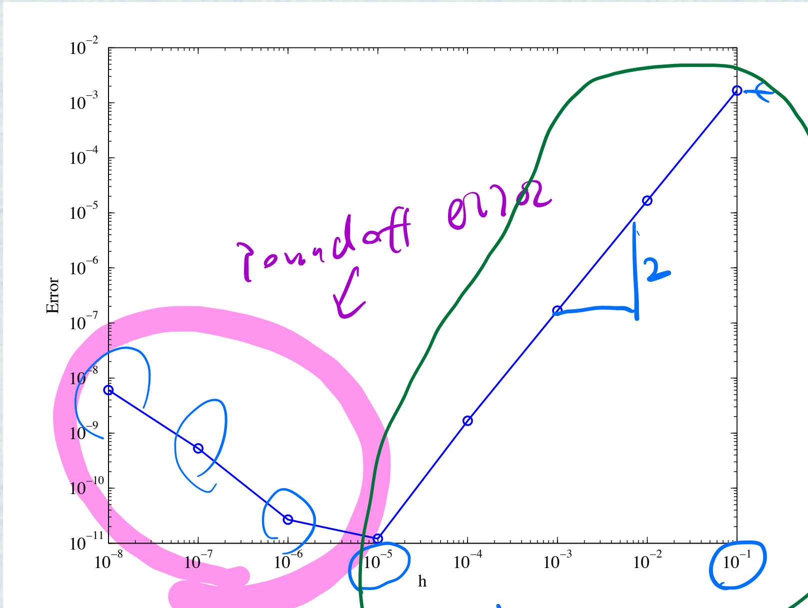
- Error increases if $h < 10^{-5}$

- Problem is cancellation error.

h
0.1
0.05
0.025
⋮

$$\varepsilon = \frac{e^h-e^{-h}}{2h} - \left.\frac{de^x}{dx}\right|_{x=0} \quad = 1$$





0.00001

← clear command window

```
clc;
clear all;
clf;

set(0,'DefaultAxesFontName', 'Times New Roman');
axes('FontSize',12);

n = 8;
h = zeros(n,1);
error = zeros(n,1);
hVal = 0;

for i=1:n
    hVal = 0.1*10^(-(i-1));
    h(i) = hVal;
    Dh = (exp(hVal)-exp(-hVal))/(2.0*hVal);
    error(i) = abs(Dh-1);
end

loglog(h,error,'-bo','LineWidth',1.25);
xlabel('h');
ylabel('Error');
```

i=1 0.1 i=2 0.01 i=3 .001

C.T.D.

Error analysis: Let $\bar{f} \equiv \mathrm{fl}(f(x))$ be the floating point representation for $f(x)$.

F.P.S

- Let $\bar{f}(x) = f(x) + e_r(x)$, where $e_r(x)$ is roundoff error bounded by double precision

machine epsilon, $\epsilon_m \leq 1 \times 10^{-16}$.

- Let $\bar{D}_h = \dfrac{\bar{f}(x_0+h) - \bar{f}(x_0-h)}{2h}$.

$$
\begin{aligned}
|\bar{D}_h - D_h| &= \left| \frac{\bar{f}(x_0+h) - \bar{f}(x_0-h)}{2h} - \frac{f(x_0+h) - f(x_0-h)}{2h} \right| \\
&= \left| \frac{e_r(x_0+h) - e_r(x_0-h)}{2h} \right| \\
&\leq \left| \frac{e_r(x_0+h)}{2h} \right| + \left| \frac{e_r(x_0-h)}{2h} \right| \leq \frac{\epsilon_m}{h}.
\end{aligned}
$$

- If $|f'''(\xi)| \leq M$ in $[x_o - h, x_0 + h]$,

$$
\begin{aligned}
|f'(x_0) - \bar{D}_h| &= \left| (f'(x_0) - D_h) + \left(D_h - \bar{D}_h\right) \right| \\
&\leq |f'(x_0) - D_h| + \left| D_h - \bar{D}_h \right| \leq \frac{h^2 M}{6} + \frac{\epsilon_m}{h}.
\end{aligned}
$$

- If h is small, ϵ_m/h term dominates.

- Should not choose h to close to the rounding unit.

- Remember that roundoff error is not smooth.

not CFD $\dfrac{f(x_0+h) - f(x_0-h)}{2h}$

Differentiating noisy data: Noise will be magnified by $1/h$.

- For the kth derivative, it will be magnified by $1/h^k$.

- Options are to filter out high frequency noise or use a least squares fit of the data before differentiating.

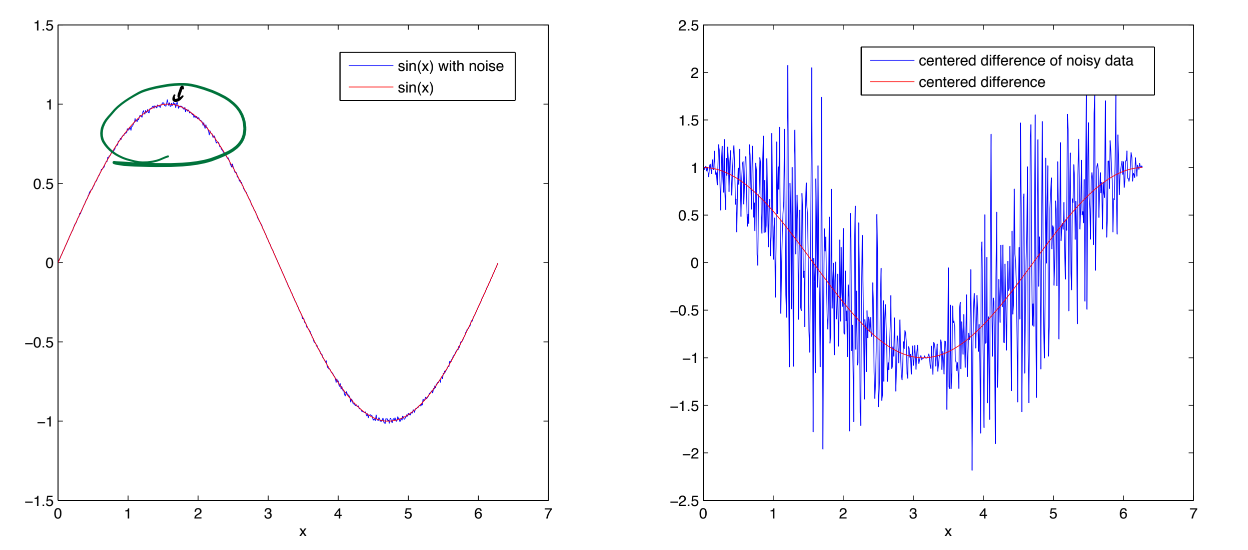
```
% Example 14.6 -- Figure 14.3 : differentiating noisy data

x = 0:.01:2*pi;
l = length(x);
sinx = sin(x);
sinp = (1+.01*randn(1,l)).*sinx;

cosx = (sinx(3:l)-sinx(1:l-2))/.02;
cosp = (sinp(3:l)-sinp(1:l-2))/.02;
err_f = max(abs(sinx-sinp))
err_fp = max(abs(cosx-cosp))

subplot(1,2,1)
plot(x,sinp,x,sinx,'r')
legend('sin(x) with noise', 'sin(x)');
xlabel('x')
%title('sin (x) with 1% noise')

subplot(1,2,2)
plot(x(2:l-1),cosp,x(2:l-1),cosx,'r')
xlabel('x')
legend('centered difference of noisy data', ...
    'centered difference ');
%title('cos (x) by noisy numerical differentiation')
```



Method of polynomial approximation

Example: Find a one-sided approximation to $f'(x_0)$ based on $f(x_0)$, $f(x_0+h)$ and $f(x_0+2h)$.

1. Approximate $f(x)$ by a degree-2 polynomial $p(x)$ with the given 3 points. Use Newton polynomial.

$$p(x) = c_0 + c_1(x - x_0) + c_2(x - x_0)(x - (x_0 + h)) \tag{11}$$

$$\begin{aligned} p(x_0) &= c_0 = f(x_0) && (12) \\ p(x_0 + h) &= c_0 + c_1 h = f(x_0 + h) && (13) \\ p(x_0 + 2h) &= c_0 + c_1(2h) + c_2(2h)(h) = f(x_0 + 2h) && (14) \end{aligned}$$

Solve the system with substitution or divided differences

$$\begin{aligned} &c_0 = f(x_0) \\ &c_1 = \frac{f(x_0+h) - f(x_0)}{h} \\ &c_2 = \frac{\frac{f(x_0+2h)-f(x_0+h)}{h} - \frac{(f(x_0+h)-f(x_0))}{h}}{2h} = \frac{f(x_0+2h) - 2f(x_0+h) + f(x_0)}{2h^2} \end{aligned}$$

Put together

$$p(x) = c_0 + c_1(x - x_1) + c_2(x - x_1)(x - x_2) = f(x_0) + \frac{f(x_0 + h) - f(x_0)}{h}(x - x_0)$$
$$+ \frac{f(x_0 + 2h) - 2f(x_0 + h) + f(x_0)}{2h^2}(x - x_0)(x - x_0 - h)$$

2. Approximate $f'(x_0)$ by

$$\begin{aligned} p'(x_0) &= c_1 + c_2(x_0 - x_1) + c_2(x_0 - x_2) = c_1 + c_2(-h) \\ &= \frac{f(x_0 + h) - f(x_0)}{h} - \frac{f(x_0 + 2h) - 2f(x_0 + h) + f(x_0)}{2h} \\ &= \frac{-3f(x_0) + 4f(x_0 + h) - f(x_0 + 2h)}{2h} \end{aligned}$$

Finite difference differentiation matrices

- Let $x_i \in [a, b]$ such that $x_0 = a$, $x_1 = a + h$, $x_i = a + ih$, $\ldots$, $x_n = b$.
- $h = (b - a)/n$.
- $f(x_i) = f_i$ is the given data.
- If we want to approximate the derivative $f'(x_i)$ using centered differences,

$$f_1' = \frac{f_2 - f_0}{2h}, \quad f_i' = \frac{f_{i+1} - f_{i-1}}{2h}, \quad f_{n-1}' = \frac{f_n - f_{n-2}}{2h}.$$

- Then we can write the operator in matrix-vector form $\mathbf{f}' = D\mathbf{f}$, where

$$\mathbf{f} = \begin{bmatrix} f(x_0) \\ f(x_1) \\ \vdots \\ f(x_n) \end{bmatrix} = \begin{bmatrix} f_0 \\ f_1 \\ \vdots \\ f_n \end{bmatrix}, \quad D = \frac{1}{2h} \begin{bmatrix} -1 & 0 & 1 & & & \\ & -1 & 0 & 1 & & \\ & & \ddots & \ddots & \ddots & \\ & & & -1 & 0 & 1 \end{bmatrix}.$$

- Dimensions of vectors and matrices?

- $\mathbf{f}'$ is uniquely determined from $\mathbf{f}$.

- Using backward differences and the condition $f(x_0) = 0$,

$$\begin{bmatrix} f'(x_1) \\ f'(x_2) \\ \vdots \\ f'(x_n) \end{bmatrix} = \frac{1}{h} \begin{bmatrix} 1 & & & \\ -1 & 1 & & \\ & \ddots & \ddots & \\ & & -1 & 1 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix}.$$

- If we are given $\mathbf{f}'$ and the initial condition, then we can solve the linear system for $\mathbf{f}$.