

PHY604 Lecture 6

September 11, 2025

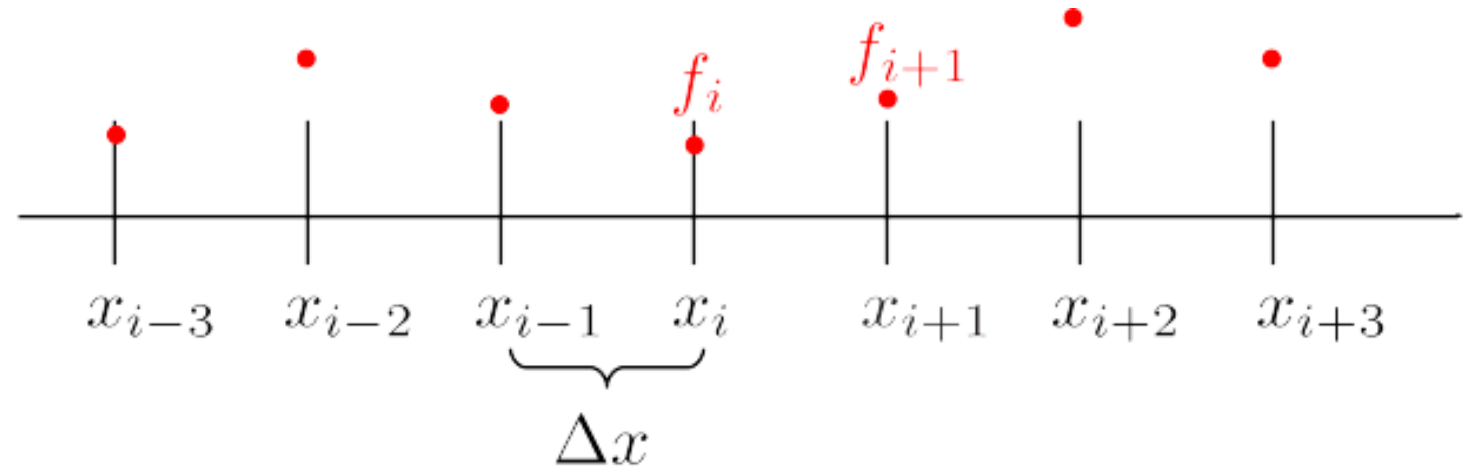
Today's lecture:

- Finish discussing interpolation
 - Cubic splines
- Root finding

Splines (Pang Sec. 2.4)

- So far, we've only worried about going through the specified points
- Large number of points → two distinct options:
 - Use a single high-order polynomial that passes through them all
 - Fit a (somewhat) high order polynomial to *each interval and match all derivatives at each point—this is a spline*
- Splines match the derivatives at end points of intervals
 - Piecewise splines can give a high-degree of accuracy
- Cubic spline is the most popular
 - Matches first and second derivative at each data point
 - Results in a smooth appearance
 - Avoids severe oscillations of higher-order polynomial

Splines



- We have a set of regular-spaced discrete data: $f_i=f(x_i)$ at $x_0, x_1, x_2, \dots, x_n$
- m -th order polynomial to approximate $f(x)$ for x in $[x_i, x_{i+1}]$:

$$p_i(x) = \sum_{k=0}^m c_{ik} x^k$$

- Coefficients chosen so $p_i(x_i)=f_i$ and from smoothness condition: all derivatives (l) match at the endpoints

$$p_i^{(l)}(x_{i+1}) = p_{i+1}^{(l)}(x_{i+1}), \quad l = 0, 1, \dots, m - 1$$

- Except for points on the boundary of the curve

Determining the coefficients

- There are n intervals; in each interval: $m+1$ coefficients for the polynomial
- Total: $(m+1)n$ coefficients:
 - Smoothness condition on interior points: $(m)(n-1)$ equations
 - Curve passing through interior points: $(n-1)$ equations
 - Remaining $m+1$ equations from imposing conditions on derivatives at end points
 - Natural spline: Setting highest-order derivative to zero at both endpoints

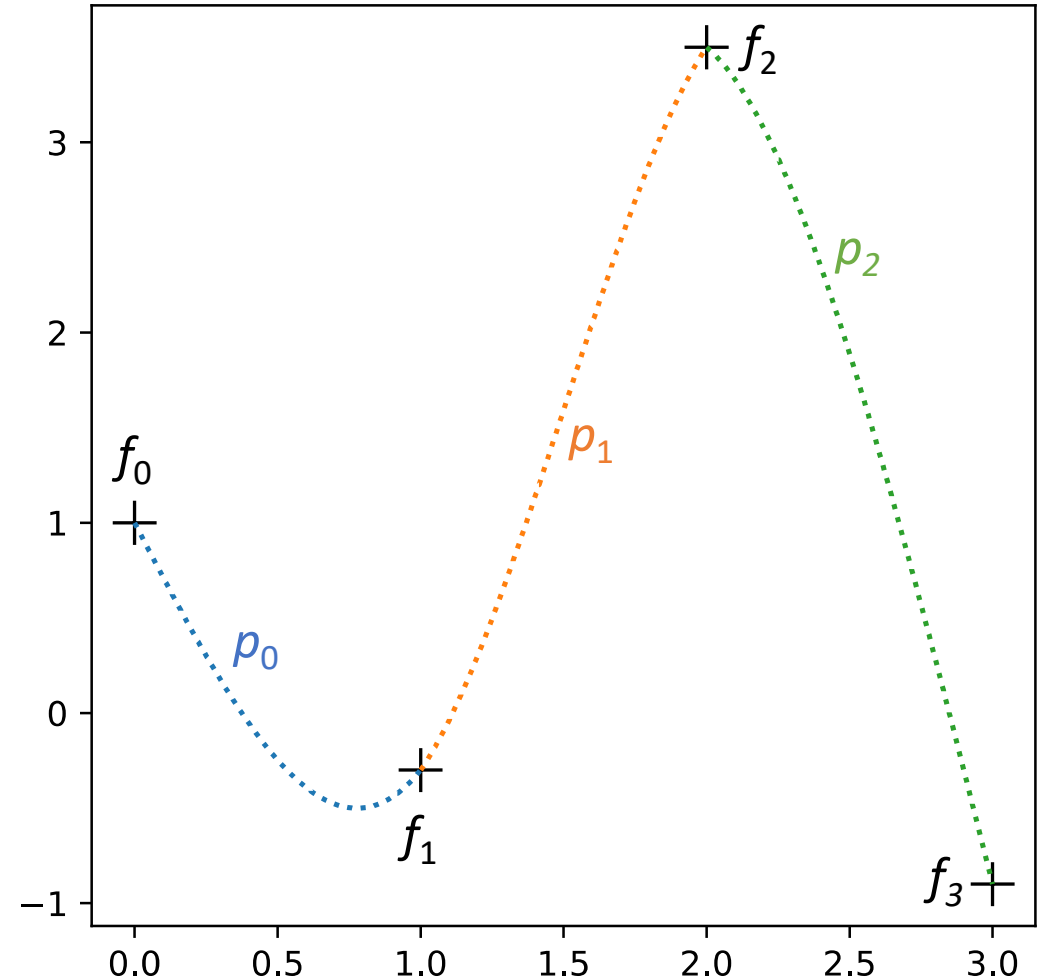
Most popular: Cubic splines, $m = 3$

- Easy to implement
- Produce a curve that appears to be seamless
- Avoids distortions near the edges
- Only piecewise continuous, third derivatives are discontinuous

Cubic spline example: 3 intervals

- Order: $m=3$, intervals: $n=3$, points: $x = 0, 1, 2, 3$
- Constraints: $(m+1)n = 12$

- Interior point 1: $p_0(x_1) = f_1$
 $p_1(x_1) = f_1$
 $p'_0(x_1) = p'_1(x_1)$
 $p''_0(x_1) = p''_1(x_1)$
- Interior point 2: $p_1(x_2) = f_2$
 $p_2(x_2) = f_2$
 $p'_1(x_2) = p'_2(x_2)$
 $p''_1(x_2) = p''_2(x_2)$



Cubic spline example: 3 intervals

- At the boundaries:

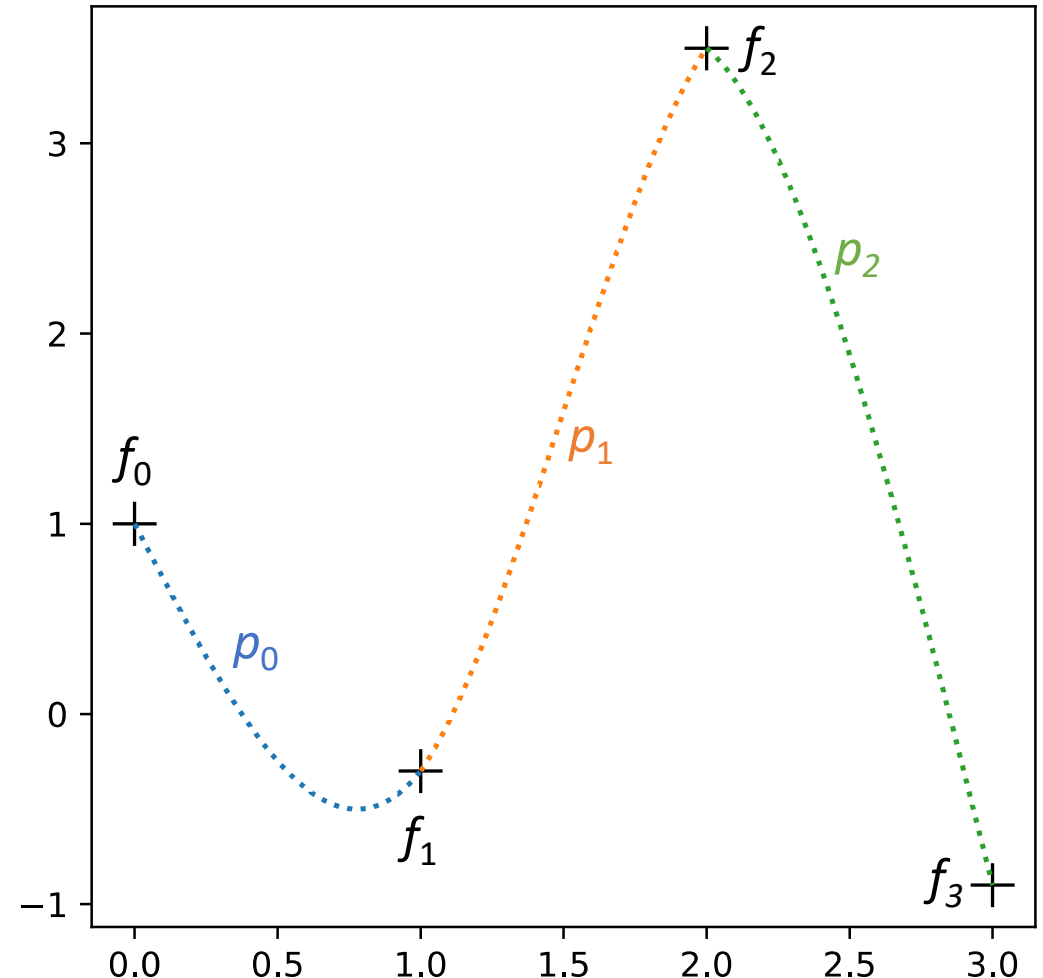
$$p_0(x_0) = f_0$$

$$p_2(x_3) = f_3$$

- Natural spline, second derivatives at the boundary set to zero

$$p_0''(x_0) = 0$$

$$p_2''(x_3) = 0$$



Now solve for the coefficients:

- Linearly interpolate the second derivative:

$$p_i''(x) = \frac{1}{\Delta x} [(x - x_i)p_{i+1}'' - (x - x_{i+1})p_i'']$$

- Integrate twice:

$$p_i(x) = \frac{1}{6\Delta x} \{ p_{i+1}'' [(x - x_i)^3 + 6A(x - x_i)] - p_i'' [(x - x_{i+1})^3 + 6B(x - x_{i+1})] \}$$

- Impose constraints: $p_i(x_i) = f_i$, $p_i(x_{i+1}) = f_{i+1}$

Now solve for the coefficients:

$$p_i(x) = \alpha_i(x - x_i)^3 + \beta_i(x - x_{i+1})^3 + \gamma_i(x - x_i) + \eta_i(x - x_{i+1})$$

- Results:

$$\alpha_i = \frac{p''_{i+1}}{6\Delta x}, \quad \beta_i = -\frac{p''_i}{6\Delta x}, \quad \gamma_i = \frac{-p''_{i+1}\Delta x^2 + 6f_{i+1}}{6\Delta x}, \quad \eta_i = \frac{p''_i\Delta x^2 - 6f_i}{6\Delta x}$$

- For now, in terms of second derivative

- To get second derivative, use continuity condition

$$p'_{i-1}(x_i) = p'_i(x_i)$$

Now solve for the coefficients:

$$p''_{i-1}\Delta x + 4p''_i\Delta x + p''_{i+1}\Delta x = \frac{6}{\Delta x}(f_{i-1} - 2f_i + f_{i+1})$$

- Applies to all interior points
- Natural boundary conditions:

$$p''_0 = 0, \quad p''_n = 0$$

- Results in a system of linear equations

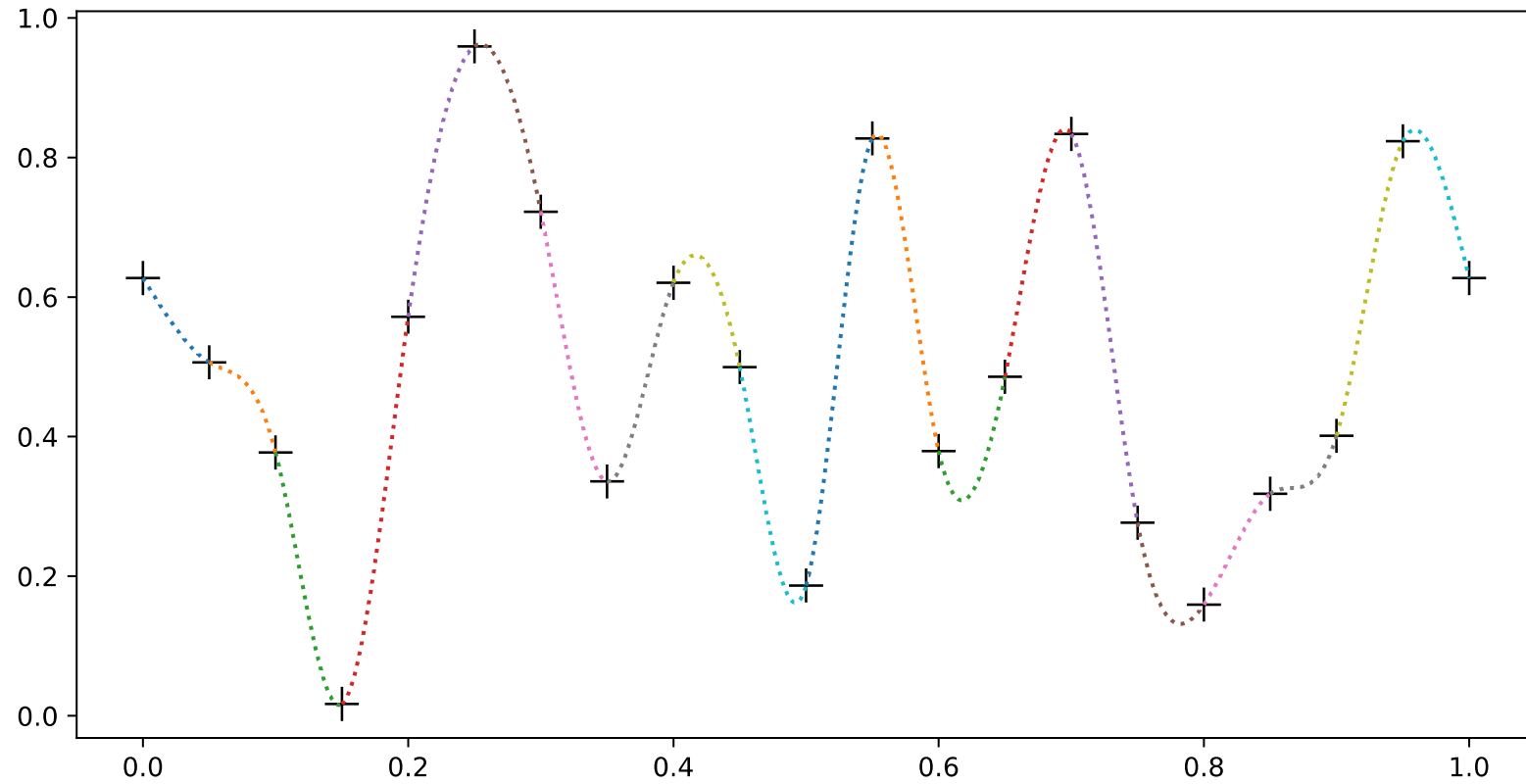
Results in system of linear equations

- Can be written as a tridiagonal matrix:

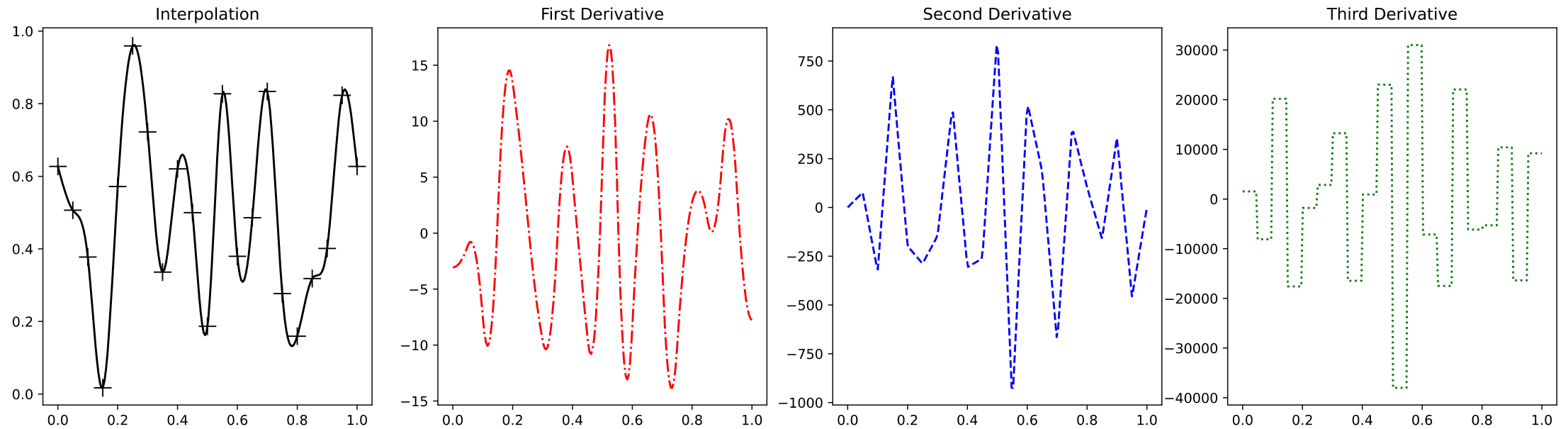
$$\begin{pmatrix} 4\Delta x & \Delta x & & & \\ \Delta x & 4\Delta x & \Delta x & & \\ & \Delta x & 4\Delta x & \Delta x & \\ & & \ddots & \ddots & \ddots \\ & & & \Delta x & 4\Delta x & \Delta x \\ & & & & \Delta x & 4\Delta x \end{pmatrix} \begin{pmatrix} p_1'' \\ p_2'' \\ p_3'' \\ \vdots \\ p_{n-2}'' \\ p_{n-1}'' \end{pmatrix} = \frac{6}{\Delta x} \begin{pmatrix} f_0 - 2f_1 + f_2 \\ f_1 - 2f_2 + f_3 \\ f_2 - 2f_3 + f_4 \\ \vdots \\ f_{n-3} - 2f_{n-2} + f_{n-1} \\ f_{n-2} - 2f_{n-1} + f_n \end{pmatrix}$$

- We will discuss linear algebra in a later class

Example: Cubic spline for random numbers



Example: Derivatives of cubic splines



Today's lecture:

- Finish discussing interpolation
 - Cubic splines
- Root finding

Purpose: Find the root of a function

- Root of a function $f(x)$ is x_r such that: $f(x_r) = 0$
- Why? We can cast more general solutions in the form of finding roots.

- Example: Suppose I have the following equation for velocity of a free-falling mass m with a coefficient of drag c_d :

$$v(t) = \sqrt{\frac{gm}{c_d}} \tanh \left(\sqrt{\frac{gc_d}{m}} t \right)$$

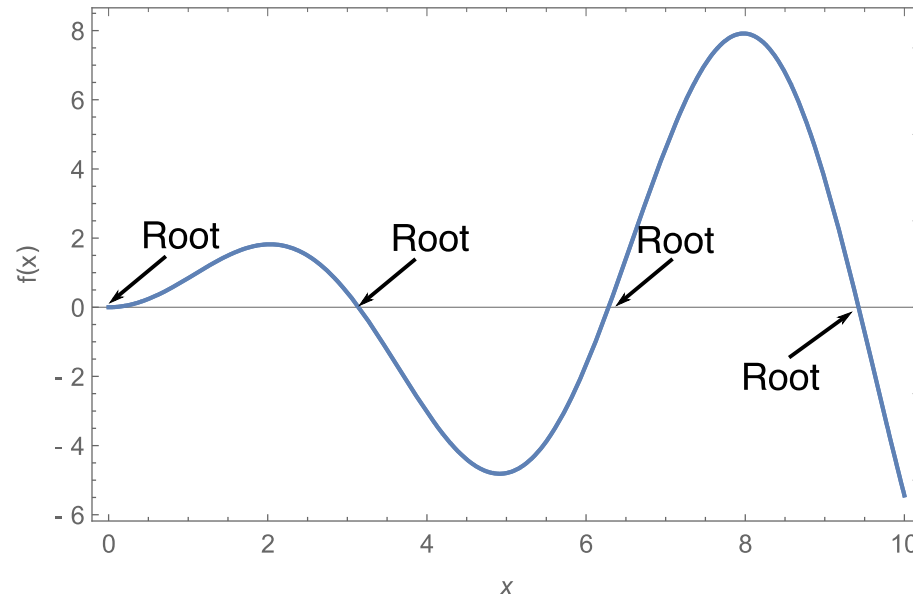
- I would like to find the mass that would give me a velocity of 36 m/s after 4s of free fall. We can do this by rewriting the equation as:

$$f(m) = \sqrt{\frac{gm}{c_d}} \tanh \left(\sqrt{\frac{gc_d}{m}} t \right) - v(t)$$

- And finding the root of $f(m)$ for $t = 4\text{s}$ and $v = 36\text{ m/s}$

Purpose: Find the root of a function

- For very simple functions, we can find the root analytically
 - For more complicated functions, we must do this numerically
- First rule of root finding: If possible, plot the function to get an idea of where roots are, how many, etc.:



Bisection method

- 1. Choose **two initial guesses** for the root, a lower (x_l) and upper (x_u)
 - Chosen such that the function evaluated at x_l and x_u have different signs
 - This can be checked by ensuring that: $f(x_l) f(x_u) < 0$

- 2. An estimate for the root is determined as the **midpoint between the guesses**

$$x_r = \frac{x_l + x_u}{2}$$

- 3. Make the following evaluations to determine in **which subinterval the root lies**, and thus obtain a refined guess:
 - If $f(x_l) f(x_r) < 0$, set $x_u = x_r$, return to step 2
 - If $f(x_l) f(x_r) > 0$, set $x_l = x_r$, return to step 2
 - If $f(x_l) f(x_r) = 0$ to some tolerance, x_r is the root and the calculation is complete

Newton-Raphson method

- Let x_r be a root of $f(x)$. Expand $f(x)$ in a Taylor series about around a **different** point x_0 that is close to x_r :

$$f(x) \simeq f(x_0) + f'(x_0)(x - x_0)$$

- Then:

$$f(x_r) = 0 \simeq f(x_0) + f'(x_0)(x_r - x_0)$$

- So:

$$x_r \simeq x_0 - \frac{f(x_0)}{f'(x_0)}$$

- Of course, this is only accurate if x_0 is close to x_r , but we can use this relation to refine the guess for the root

Newton-Raphson method procedure

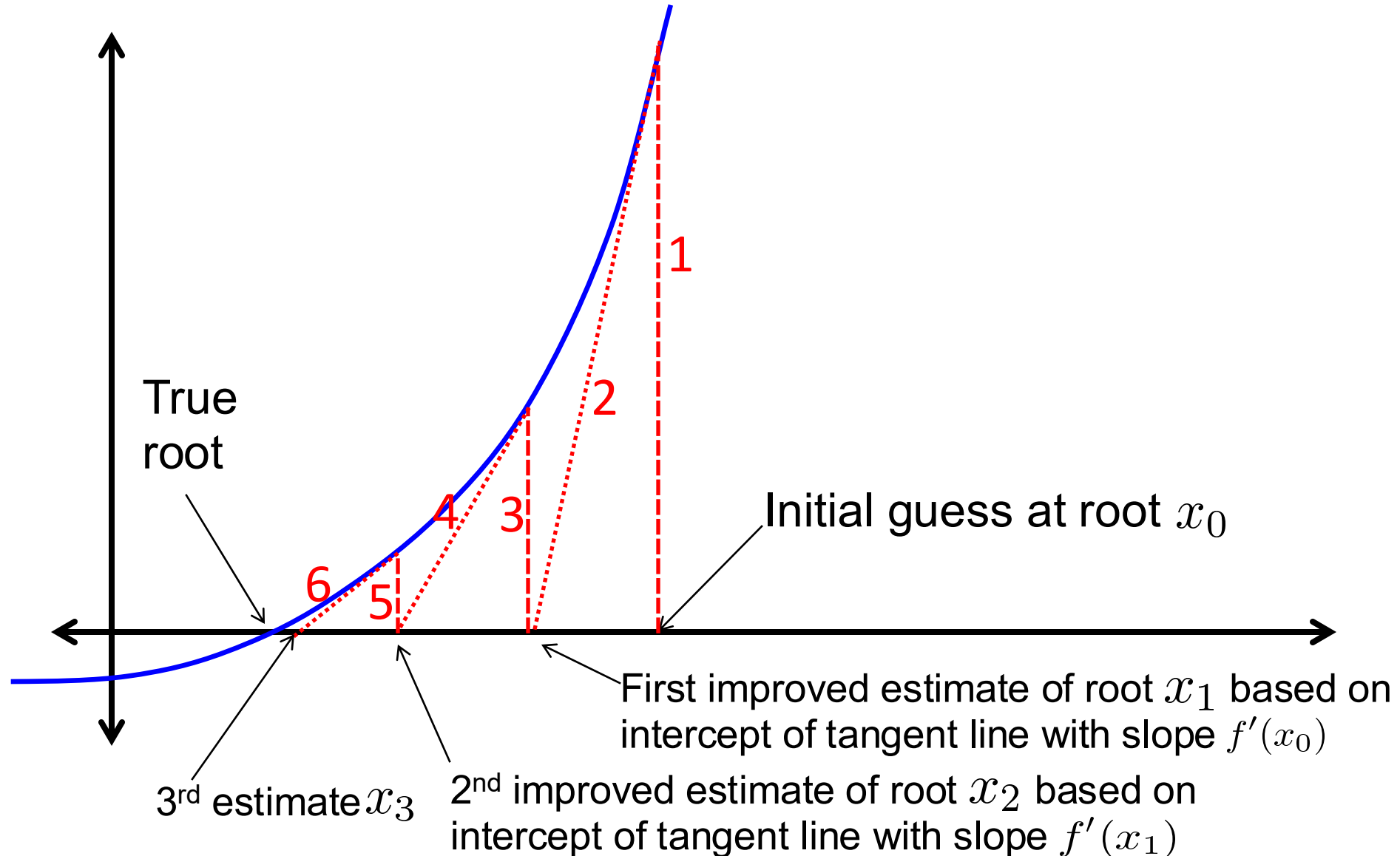
- 1. Make an **initial guess** for the root: x_0
- 2. Use the Taylor series expansion to **find a better estimate** of the root:

$$x_1 \simeq x_0 - \frac{f(x_0)}{f'(x_0)}$$

- 3. Use x_1 as an improved estimate at the root and employ the Taylor series expansion again to get a better estimate x_2
- Repeat process until the answer is accurate enough at the n th estimate:

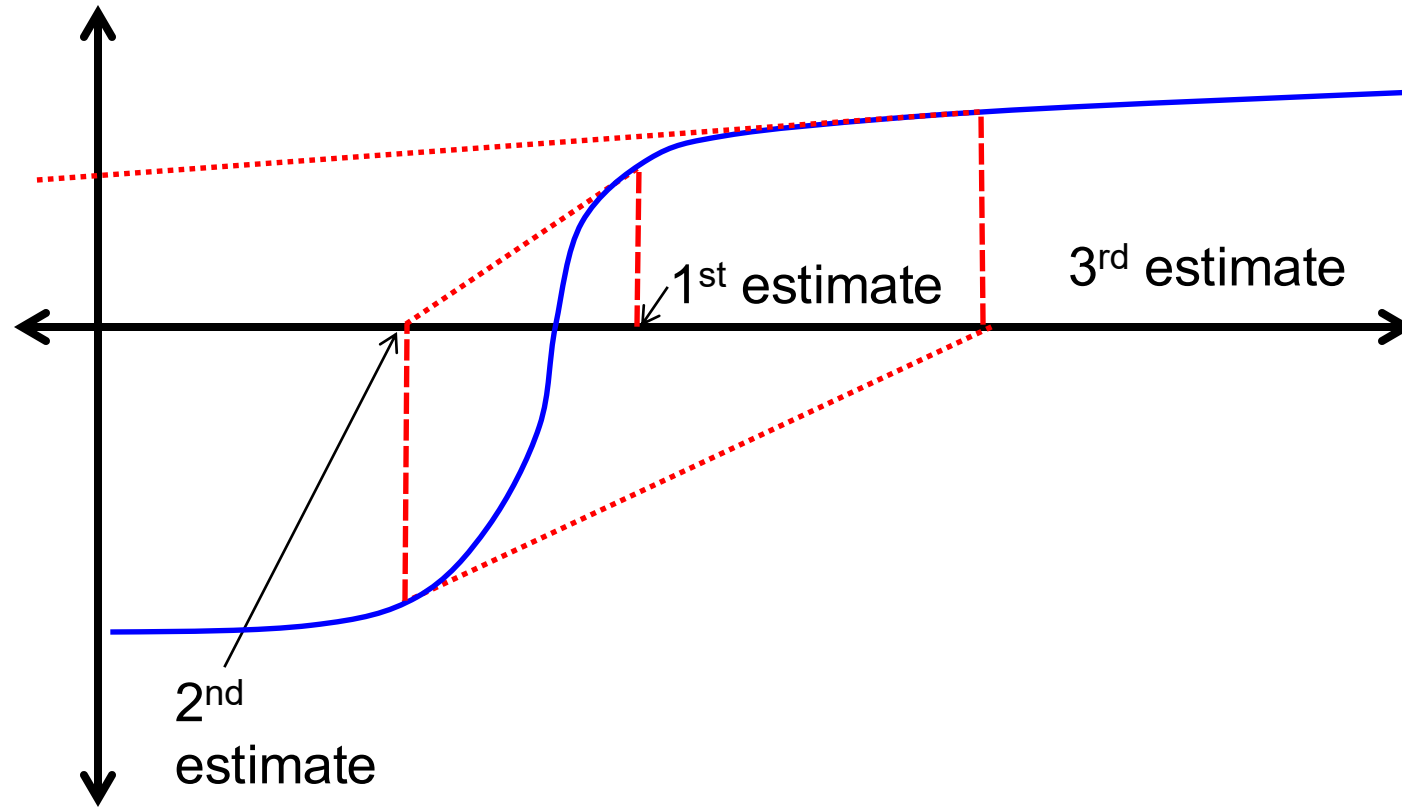
$$x_n \simeq x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})}$$

Geometrical Interpretation of Newton-Raphson Iteration



Failure of Newton-Raphson

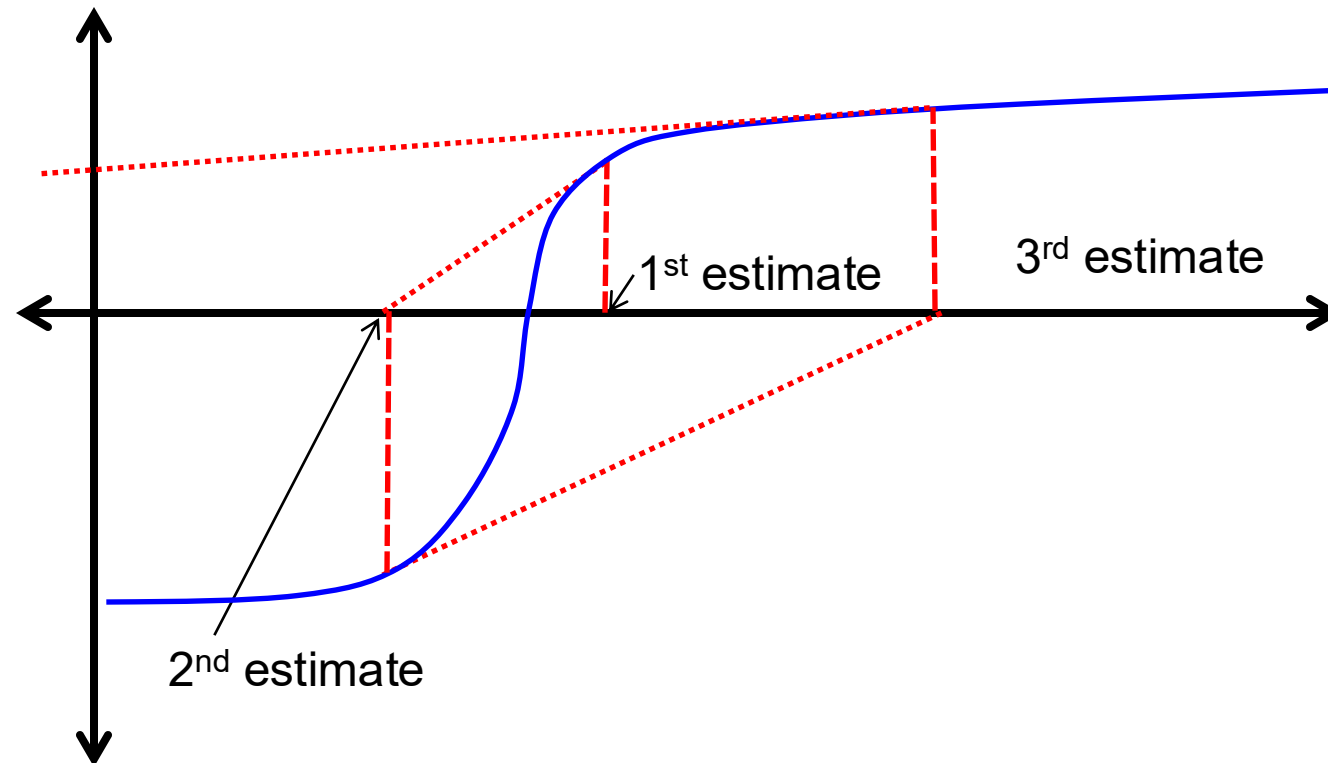
- Example of a simple function that will defeat Newton-Raphson Iteration:



- Each estimate gets further from the true root. Estimates are diverging not converging

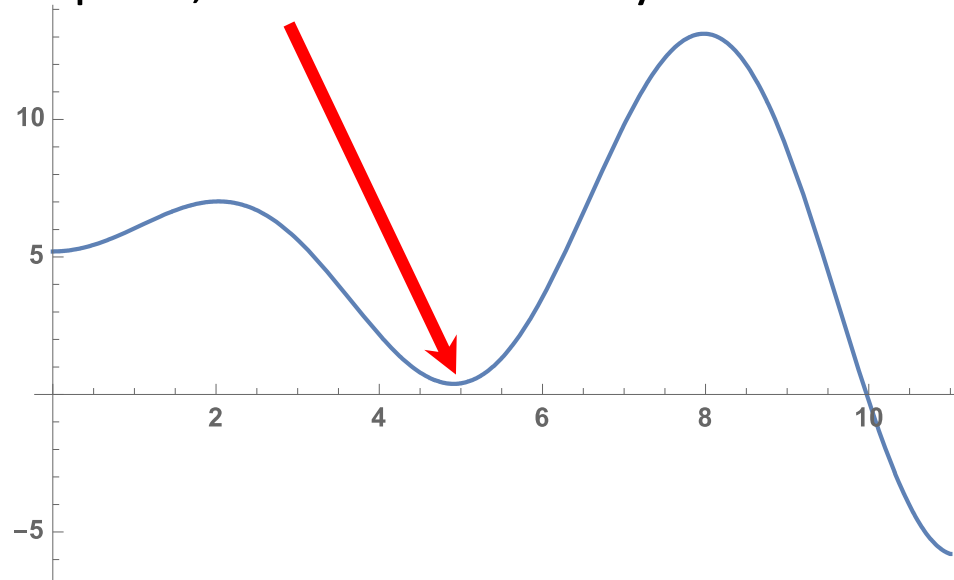
Stopping criteria for iterations must be chosen carefully

- Could stop when we reach some **maximum number of iterations**
 - Estimate may be no where near the root
 - We can consider this case a failure of the method and warn user about it.



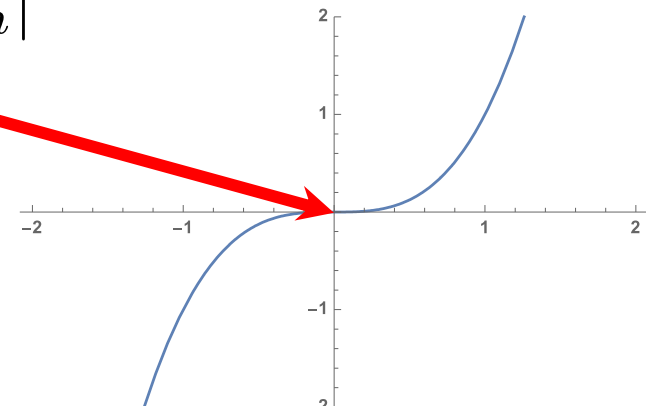
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- Could stop when **value of the function** evaluated at the n th estimate **less than small number** : $|f(x_n)| < \epsilon$
 - But this can be deceptive; final estimate may not be near the root, might just be close to zero



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 - Better, but still fails when root is located at zero



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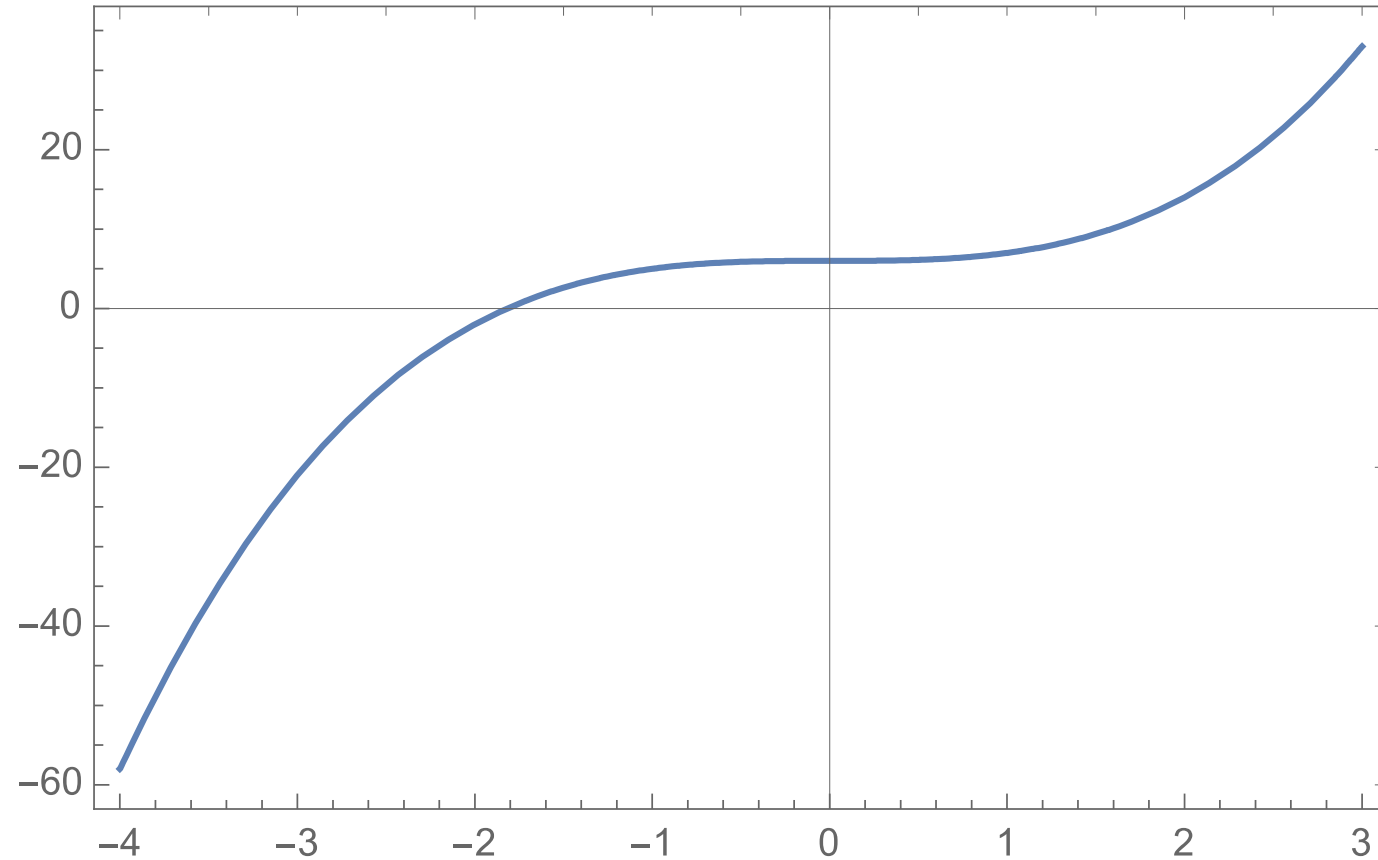
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- Could stop when **change between estimates becomes small** relative to the current (n th) estimate: $|x_{n+1} - x_n| < \epsilon|x_n|$
 - Better, but still fails when root is located at zero
- So let's use:
$$|x_{n+1} - x_n| < \begin{cases} \epsilon|x_n|, & \text{when } |x_n| \neq 0 \\ \epsilon, & \text{when } |x_n| = 0 \end{cases}$$

Pseudocode of Newton-Raphson Algorithm

- 1. Choose initial guess at the root (x_0), and the convergence tolerance (ε).
- 2. Loop through n up to a maximum number N_{\max} (exit and tell the user that the root finding has failed if it reaches N_{\max})
- 3. Make sure $f'(x) \neq 0$
- 4. Compute new estimate of root: $x_n \simeq x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})}$
- 5. Check convergence criteria:

$$|x_{n+1} - x_n| < \begin{cases} \varepsilon |x_n|, & \text{when } |x_n| \neq 0 \\ \varepsilon, & \text{when } |x_n| = 0 \end{cases}$$

Example: $f(x) = x^3 + 6$



- See [NR_root.ipynb](#)

Secant method

- Similar to the Newton-Raphson method, but does not require calculating the derivative of the function
- Start with two initial guesses, x_{i-1} and x_i
- Use finite difference derivative to get a new guess x_{i+1}

$$x_{i+1} = x_i - \frac{f(x_i)(x_{i-1} - x_i)}{f(x_{i-1}) - f(x_i)}$$

- Proceed in the same way as the Newton-Raphson method

Summary of root-finding methods

- Bisection:
 - Robust (with appropriate initial guesses)
 - Slow, each iteration reduces error by a factor of two
 - Need to make sure root is within initial guesses
- Newton-Raphson:
 - Fast: often only takes a few iterations
 - Need to know derivative of function, and they must exist
 - Can diverge, e.g., in cases with small second derivatives
- Secant method
 - Similar convergence speed as NR method
 - Don't need analytical derivatives
 - Same divergence properties as NR method
 - Numerical derivatives may be noisy

After class tasks

- Readings:
 - Pang Section 2.1 and 3.3
 - [Wikipedia page on root finding](#)