Numerical Analysis and Computing

Lecture Notes #3 — Solutions of Equations in One Variable: Fixed Point Iteration; Root Finding; Error Analysis for Iterative Methods

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Outline

1. Root Finding
   - Fixed Point Iteration
   - Detour: — Non-unique Fixed Points...

2. Improved Algorithms for Root Finding
   - Newton’s Method
   - The Secant Method
   - The Regula Falsi Method
   - Quick Summary

3. Error Analysis
   - Convergence
   - Practical Application of the Theorems
   - Roots of Higher Multiplicity
Quick Recap

Last time we looked at the **method of bisection** for finding the root of the equation $f(x) = 0$.

Now, we are take a short detour in order to explore how

**Root finding:** $f(x) = 0$,

is related to

**Fixed point iteration:** $f(p) = p$. 
Fixed Point Iteration $\iff$ Root Finding

If $f(p) = p$, then we say that $p$ is a **fixed point** of the function $f(x)$. We note a strong relation between root finding and finding fixed points:
Fixed Point Iteration $\iff$ Root Finding

If $f(p) = p$, then we say that $p$ is a **fixed point** of the function $f(x)$. We note a strong relation between root finding and finding fixed points:

To convert a fixed-point problem

$$g(x) = x,$$

to a root finding problem, define

$$f(x) = g(x) - x,$$

and look for roots of $f(x) = 0$. 

Joe Mahaffy, \{mahaffy@math.sdsu.edu\}  Solutions of Equations in One Variable  — (4/57)
Fixed Point Iteration ⇔ Root Finding

If \( f(p) = p \), then we say that \( p \) is a **fixed point** of the function \( f(x) \). We note a strong relation between root finding and finding fixed points:

To convert a fixed-point problem

\[
g(x) = x,
\]

to a root finding problem, define

\[
f(x) = g(x) - x,
\]

and look for roots of \( f(x) = 0 \).

To convert a root finding problem

\[
f(x) = 0,
\]

to a fixed point problem, define

\[
g(x) = f(x) + x,
\]

and look for fixed points \( g(x) = x \).

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If fixed point iterations are (in some sense) equivalent to root finding, why not just stick to root finding???

1. Sometimes easier to analyze.

2. What we learn from the analysis will help us find good root finding strategies.

3. Fixed point iterations pose some “cute” problems by themselves.
Example: The Bored Student Fixed Point

A “famous” fixed point is $p = 0.73908513321516$ (radians), i.e. the number you get by repeatedly hitting $\cos$ on a calculator. This number solves the fixed point equation:

$$\cos(p) = p$$

With a starting value of $p = 0.3$ we get:

Iteration #1:
$p = 0.3$,
$\cos(p) = 0.92106099400289$
Example: The Bored Student Fixed Point

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\[
\cos(p) = p
\]

With a starting value of \( p = 0.3 \) we get:

Iteration #2:
\[
p = 0.92106099400289, \quad \cos(p) = 0.60497568726594
\]
Example: The Bored Student Fixed Point

A “famous” fixed point is \( p = 0.73908513321516 \) (radians), i.e. the number you get by repeatedly hitting \( \cos \) on a calculator. This number solves the fixed point equation:

\[
\cos(p) = p
\]

With a starting value of \( p = 0.3 \) we get:

\[
\begin{align*}
&\text{Iteration \#2:} \\
&p = 0.92106099400289, \\
&\cos(p) = 0.60497568726594 \\
&p = 0.60497568726594
\end{align*}
\]
Example: The Bored Student Fixed Point

A “famous” fixed point is \( p = 0.73908513321516 \) (radians), i.e. the number you get by repeatedly hitting \( \cos \) on a calculator. This number solves the fixed point equation:

\[
\cos(p) = p
\]

With a starting value of \( p = 0.3 \) we get:

\[
\begin{align*}
\text{Iteration \#3:} \\
p &= 0.60497568726594, \\
\cos(p) &= 0.82251592555039
\end{align*}
\]
Example: The Bored Student Fixed Point

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$$\cos(p) = p$$

With a starting value of $p = 0.3$ we get:

Iteration #4:
$p = 0.82251592555039$,
$\cos(p) = 0.68037954156567$
Example: The Bored Student Fixed Point

A “famous” fixed point is $p = 0.73908513321516$ (radians), i.e. the number you get by repeatedly hitting $\cos$ on a calculator. This number solves the fixed point equation:

$$\cos(p) = p$$

With a starting value of $p = 0.3$ we get:

Iteration #4:

$p = 0.82251592555039$, $\cos(p) = 0.68037954156567$, $p = 0.68037954156567$
Example: The Bored Student Fixed Point

A “famous” fixed point is \( p = 0.73908513321516 \) (radians), i.e. the number you get by repeatedly hitting \( \cos \) on a calculator. This number solves the fixed point equation:

\[
\cos(p) = p
\]

With a starting value of \( p = 0.3 \) we get:

Iteration #5:
\[
p = 0.68037954156567, 
\cos(p) = 0.77733400966246
\]
Example: The Bored Student Fixed Point

A “famous” fixed point is $p = 0.73908513321516$ (radians), i.e. the number you get by repeatedly hitting $\cos$ on a calculator. This number solves the fixed point equation:

$$\cos(p) = p$$

With a starting value of $p = 0.3$ we get:

Iteration #5:

$p = 0.68037954156567$, $\cos(p) = 0.77733400966246$

$p = 0.77733400966246$
Example: The Bored Student Fixed Point

A “famous” fixed point is \( p = 0.73908513321516 \) (radians), i.e. the number you get by repeatedly hitting \( \cos \) on a calculator. This number solves the fixed point equation:

\[
\cos(p) = p
\]

With a starting value of \( p = 0.3 \) we get:

\[
\begin{align*}
\text{Iteration \#6:} \\
p &= 0.77733400966246, \\
\cos(p) &= 0.71278594551835
\end{align*}
\]
Example: The Bored Student Fixed Point

A “famous” fixed point is \( p = 0.73908513321516 \) (radians), i.e. the number you get by repeatedly hitting \( \cos \) on a calculator. This number solves the fixed point equation:

\[
\cos(p) = p
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With a starting value of \( p = 0.3 \) we get:

Iteration #6:
\[
\begin{align*}
p &= 0.77733400966246, \\
\cos(p) &= 0.71278594551835 \\
p &= 0.71278594551835
\end{align*}
\]
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\[
\cos(p) = p
\]

With a starting value of \( p = 0.3 \) we get:

Iteration \#7:
\[
\begin{align*}
p &= 0.71278594551835, \\
\cos(p) &= 0.75654296195845
\end{align*}
\]
Example: The Bored Student Fixed Point

A “famous” fixed point is \( p = 0.73908513321516 \) (radians), i.e. the number you get by repeatedly hitting \( \cos \) on a calculator. This number solves the fixed point equation:

\[
\cos(p) = p
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With a starting value of \( p = 0.3 \) we get:

Iteration #7:
\[
\begin{align*}
 p &= 0.71278594551835, \\
 \cos(p) &= 0.75654296195845 \\
 p &= 0.75654296195845
\end{align*}
\]
When Does Fixed-Point Iteration Converge?

The following theorem tells us when a fixed point exists:

### Theorem (Convergence of Fixed Point Iteration)

1. If \( f \in C[a, b] \) and \( f(x) \in [a, b] \), \( \forall x \in [a, b] \), then \( f \) has a fixed point \( p \in [a, b] \). (Brouwer fixed point theorem)

2. If, in addition, the derivative \( f'(x) \) exists on \( (a, b) \) and \( |f'(x)| \leq k < 1 \), \( \forall x \in (a, b) \), then the fixed point is unique. (Contraction Mapping Principle)

How does this apply to \( \cos(x) \)???

### Note 1:

\( f \in C[a, b] \) — “\( f \) is continuous in the interval \([a, b]\).” (input)

### Note 2:

\( f(x) \in [a, b] \) — “\( f \) takes values in \([a, b]\).” (output)
a. If \( f(a) = a \), or \( f(b) = b \), then we are done.

Otherwise, \( f(a) > a \) and \( f(b) < b \).
Proof of the Fixed Point Theorem

a. If \( f(a) = a \), or \( f(b) = b \), then we are done.

Otherwise, \( f(a) > a \) and \( f(b) < b \).

We define a new function \( h(x) = f(x) - x \).

Since both \( f(x) \) and \( x \) are continuous, we have \( h(x) \in C[a, b] \), further \( h(a) > 0 \), and \( h(b) < 0 \) by construction.
Proof of the Fixed Point Theorem

a. If \( f(a) = a \), or \( f(b) = b \), then we are done.

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Since both \( f(x) \) and \( x \) are continuous, we have \( h(x) \in C[a, b] \), further \( h(a) > 0 \), and \( h(b) < 0 \) by construction.

Now, the **intermediate value theorem** guarantees \( \exists p^* \in (a, b): h(p^*) = 0 \).

We have \( 0 = h(p^*) = f(p^*) - p^* \), or \( p^* = f(p^*) \).
b. $|f'(x)| \leq k < 1$. Suppose we have two fixed points $p^* \neq q^*$. Without loss of generality we may assume $p^* < q^*$.

The **mean value theorem** tells us $\exists r \in (p^*, q^*)$:

$$f'(r) = \frac{f(p^*) - f(q^*)}{p^* - q^*}$$
b. $|f'(x)| \leq k < 1$. Suppose we have two fixed points $p^* \neq q^*$. Without loss of generality we may assume $p^* < q^*$.

The **mean value theorem** tells us $\exists r \in (p^*, q^*)$:

$$f'(r) = \frac{f(p^*) - f(q^*)}{p^* - q^*}$$

Now,

$$|p^* - q^*| = |f(p^*) - f(q^*)|$$
$$= |f'(r)| \cdot |p^* - q^*|$$
$$\leq k|p^* - q^*|$$
$$< |p^* - q^*|$$
b. $|f'(x)| \leq k < 1$. Suppose we have two fixed points $p^* \neq q^*$. Without loss of generality we may assume $p^* < q^*$.

The **mean value theorem** tells us $\exists r \in (p^*, q^*)$:

$$f'(r) = \frac{f(p^*) - f(q^*)}{p^* - q^*}$$

Now,

$$|p^* - q^*| = |f(p^*) - f(q^*)|$$

$$= |f'(r)| \cdot |p^* - q^*|$$

$$\leq k|p^* - q^*|$$

$$< |p^* - q^*|$$

The contradiction $|p^* - q^*| < |p^* - q^*|$ shows that the supposition $p^* \neq q^*$ is false. Hence, the fixed point is unique.
Convergence of the Fixed Point Sequence

Or, “how come hitting $\cos$ converges???”

Take a look at the theorem we just proved

— part (a) guarantees the existence of a fixed point.
— part (b) tells us when the fixed point is unique.

We have no information about finding the fixed point!

We need one more theorem — one which guarantees us that we can find the fixed point!
Suppose both part (a) and part (b) of the previous theorem (here restated) are satisfied:

**Theorem (Convergence of Fixed Point Iteration)**

a. If \( f \in C[a, b] \) and \( f(x) \in [a, b] \), \( \forall x \in [a, b] \), then \( f \) has a fixed point \( p \in [a, b] \). (Brouwer fixed point theorem)

b. If, in addition, the derivative \( f'(x) \) exists on \( (a, b) \) and \( |f'(x)| \leq k < 1 \), \( \forall x \in (a, b) \), then the fixed point is unique.

c. Then, for any number \( p_0 \in [a, b] \), the sequence defined by

\[
p_n = f(p_{n-1}), \quad n = 1, 2, \ldots, \infty
\]

converges to the unique fixed point \( p^* \in [a, b] \).
That’s great news! — We can use any starting point, and we are guaranteed to find the fixed point.

The proof is straight-forward:

\[
|p_n - p^*| = |f(p_{n-1}) - f(p^*)| \\
= |f'(r)| \cdot |p_{n-1} - p^*| \quad \text{by \{MVT\}} \\
\leq k|p_{n-1} - p^*| \quad \text{by } b
\]

Since \( k < 1 \), the distance to the fixed point is shrinking every iteration.

In fact,

\[
|p_n - p^*| \leq k^n|p_0 - p^*| \leq k^n \max \{p_0 - a, b - p_0\}.
\]
Example: \( x^3 + 4x^2 - 10 = 0 \)

The equation \( x^3 + 4x^2 - 10 = 0 \) has a unique root in the interval \([1, 2]\).

We make a couple attempts at finding the root:

1. Define \( g_1(x) = x^3 + 4x^2 - 10 + x \), and try to solve \( g_1(x) = x \).
   
   This fails since \( g_1(1) = -4 \), which is outside the interval \([1, 2]\).
Example: \( x^3 + 4x^2 - 10 = 0 \)

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2. Define \( g_2(x) = \sqrt{10/x - 4x} \), and try to solve \( g_2(x) = x \).
   This fails since \( g_2(x) \) is not defined (or complex) at \( x = 2 \).
Example: \( x^3 + 4x^2 - 10 = 0 \)

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2. Define \( g_2(x) = \sqrt{10/x - 4x} \), and try to solve \( g_2(x) = x \).
   This fails since \( g_2(x) \) is not defined (or complex) at \( x = 2 \).

3. It turns out that the best form is solving \( x = g_3(x) \), where

\[
g_3(x) = x - \frac{x^3 + 4x^2 - 10}{3x^2 + 8x},
\]

that’s probably not obvious at first glance!!!  (Continued...)
Example: \( x^3 + 4x^2 - 10 = 0 \)

Iteration #1:
\[ p = 1, \]
\[ p^3 + 4p^2 - 10 = -5.0000 \]
\[ g_3(p) = 1.4545 \]
Example: \( x^3 + 4x^2 - 10 = 0 \)

Iteration #1:
- \( p = 1 \),
- \( p^3 + 4p^2 - 10 = -5.0000 \)
- \( g_3(p) = 1.4545 \)
- \( p = 1.4545 \)
Example: $x^3 + 4x^2 - 10 = 0$

Iteration #2:
$p = 1.4545$,
$p^3 + 4p^2 - 10 = 1.5402$
$g_3(p) = 1.3689$
Example: \( x^3 + 4x^2 - 10 = 0 \)

Iteration #2:
\[ p = 1.4545, \]
\[ p^3 + 4p^2 - 10 = 1.5402 \]
\[ g_3(p) = 1.3689 \]
\[ p = 1.3689 \]
Example: \( x^3 + 4x^2 - 10 = 0 \)

Iteration #3:
\[
p = 1.3689, \\
p^3 + 4p^2 - 10 = 0.0607 \\
g_3(p) = 1.3652
\]
Example: \( x^3 + 4x^2 - 10 = 0 \)

Iteration #3:
\[
p = 1.3689,
\]
\[
p^3 + 4p^2 - 10 = 0.0607
\]
\[
g_3(p) = 1.3652
\]
\[
p = 1.3652
\]
Example: \( x^3 + 4x^2 - 10 = 0 \)

**Iteration #4:**
\[
p = 1.3652,
\]
\[
p^3 + 4p^2 - 10 = 0.0001
\]
\[
g_3(p) = 1.3652
\]
Example: \( x^3 + 4x^2 - 10 = 0 \)

Iteration #4:
\[
p = 1.3652, \\
p^3 + 4p^2 - 10 = 0.0001 \\
g_3(p) = 1.3652 \\
p = 1.3652
\]

How did we come up with this crazy function \( g_3(x) \)??
It will be explained in the next section (on Newton’s method).

The bottom line is that without more analysis, it is extremely hard to find the best (or even a functioning) fixed point iteration which finds the correct solution.
Strange, and sometimes beautiful things happen when part (a) (existence) of the fixed-point theorem is satisfied, but part (b) is not...

Let us consider the family of functions $f_a(x)$ parametrized by $a$, defined as

$$f_a(x) = 1 - ax^2, \quad x \in [-1, 1]$$
Strange, and sometimes beautiful things happen when part (a) (existence) of the fixed-point theorem is satisfied, but part (b) is not...

Let us consider the family of functions $f_a(x)$ parametrized by $a$, defined as

$$f_a(x) = 1 - ax^2, \quad x \in [-1, 1]$$

Given a particular value of $a$, the fixed point iteration

$$x_n = f_a(x_{n-1}) = 1 - ax_{n-1}^2$$

has a fixed point for values of $a \in [0, 2]$. 
By solving the quadratic equation, \( ax^2 + x - 1 = 0 \), we get the fixed point to be

\[
p^* = -\frac{1 - \sqrt{1 + 4a}}{2a}
\]

the other root is outside the interval \([-1, 1]\).
By solving the quadratic equation, \( ax^2 + x - 1 = 0 \), we get the fixed point to be

\[
p^* = -\frac{1 - \sqrt{1 + 4a}}{2a}
\]

the other root is outside the interval \([-1, 1]\).

The derivative of \( f_a(x) = 1 - ax^2 \) at the fixed point is:

\[
f_a'(p^*) = -2a \left[ \frac{1 - \sqrt{1 + 4a}}{2a} \right] = \sqrt{1 + 4a} - 1 > 0
\]

\[
|f_a'(p^*)| = \sqrt{1 + 4a} - 1
\]

as long as \( a < \frac{3}{4} \) we have \( |f_a'(p^*)| < 1 \), but something definitely breaks when \( a > \frac{3}{4} \)...
Non-uniqueness of the Fixed Point

Let’s look at the theoretical fixed point, and the computed values of the fixed point iteration... for values of \( a \) between 0 and 1.

Indeed, something strange happened around \( a = 0.75 \).
It turns out that when $|f'(p^*)| > 1$ the fixed point exists, but is no longer “attractive,” i.e. the fixed point iteration does not converge to it.
Non-uniqueness of the Fixed Point

It turns out that when \(|f'(p^*)| > 1\) the fixed point exists, but is no longer “attractive,” i.e. the fixed point iteration does not converge to it.

Instead we settled in to a 2-orbit; — where the iteration “jumps” between the upper and lower branches of the diagram.

It turns out that the function

\[ f_a^2(x) \equiv f_a(f_a(x)) = 1 - a(1 - ax^2)^2 \]

has a unique fixed point for \(a\) in the range \([0.75, 1]\) (at least).

For some other critical value of \(a\), the fixed point for \(f_a(f_a(x))\) (the 2-orbit of \(f_a(x)\)) also becomes unstable... it breaks into a 4-orbit.
We see how iterations of $f_a(x)$ go from fixed-points, to 2-orbits, to 4-orbits...
Non-uniqueness of the Fixed Point

As we may imagine, a 4-orbit corresponds to an attractive (stable) fixed point for the function \( f_a^4(x) \equiv f_a^2(f_a^2(x)) \equiv f_a(f_a(f_a(f_a(x)))) \).

It turns out we can play this game “forever...”

![Bifurcation Diagram for \( f(x)=1-ax^2 \)](image-url)
The analysis of such “bifurcation diagrams” is done in Math 538 “Dynamical Systems and Chaos...”

The dynamics of $f_a(x) = 1 - ax^2$ is one of the simplest examples of chaotic behavior in a system.
So far we have looked at two algorithms:

1. Bisection for **root finding**.
2. Fixed point iteration.

We have see that fixed point iteration and root finding are strongly related, but it is not always easy to find a good fixed-point formulation for solving the root-finding problem.

In the next section we will add three new algorithms for root finding:

1. Regula Falsi
2. Secant Method
3. Newton’s Method
Recall: we are looking for $x^*$ so that $f(x^*) = 0$.

If $f \in C^2[a, b]$, and we know $x^* \in [a, b]$ (possibly by the intermediate value theorem), then we can formally Taylor expand around a point $x$ close to the root:

$$0 = f(x^*) = f(x) + (x^* - x)f'(x) + \frac{(x - x^*)^2}{2} f''(\xi(x)), \quad \xi(x) \in [x, x^*]$$

If we are close to the root, then $|x - x^*|$ is small, which means that $|x - x^*|^2 \ll |x - x^*|$, hence we make the approximation:

$$0 \approx f(x) + (x^* - x)f'(x), \quad \Leftrightarrow \quad x^* \approx x - \frac{f(x)}{f'(x)}$$
Newton’s Method for root finding is based on the approximation

\[ x^* \approx x - \frac{f(x)}{f'(x)} \]

which is valid when \( x \) is close to \( x^* \).
Newton’s Method for root finding is based on the approximation

\[ x^* \approx x - \frac{f(x)}{f'(x)} \]

which is valid when \( x \) is close to \( x^* \).

We use the above in the following way: given an approximation \( x_{n-1} \), we get an \textbf{improved approximation} \( x_n \) by computing

\[ x_n = x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})} \]

Geometrically, \( x_n \) is the intersection of the tangent of the function at \( x_{n-1} \) and the \( x \)-axis.
Two Steps of Newton for \( f(x) = x^3 + 4x^2 - 10 = 0 \)

\[
p_0 = 1
\]

\[
p_1 = p_0 - \frac{p_0^3 + 4p_0^2 - 10}{3p_0^2 + 8p_0} = 1.45454545454545
\]

\[
p_2 = p_1 - \frac{p_1^3 + 4p_1^2 - 10}{3p_1^2 + 8p_1} = 1.36890040106952
\]
The Pros and Cons of Newton’s Method

**Strategy: Newton’s Method**

\[ x_n = x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})} \]

**Fast convergence:** Newton’s method converges the fastest of the methods we explore today. (Quadratic convergence).

Clearly, points where \( f'(\cdot) = 0 \) will cause problems!

It is especially problematic if \( f(x^*) = f'(x^*) = 0 \) — we cannot avoid the point where \( f'(\cdot) = 0 \) in this case; it is the point we are looking for!

Newton’s method work best if \( f'(\cdot) \geq k > 0 \).

**“Expensive:”** We have to compute the derivative in every iteration.
Finding a Starting Point for Newton’s Method

Recall our initial argument that when \(|x - x^*|\) is small, then 
\(|x - x^*|^2 \ll |x - x^*|\), and we can neglect the second order term in the Taylor expansion.

In order for Newton’s method to converge we need a **good starting point**!

**Theorem**

Let \(f(x) \in C^2[a, b]\). If \(x^* \in [a, b]\) such that \(f(x^*) = 0\) and \(f'(x^*) \neq 0\), then there exists a \(\delta > 0\) such that Newton’s method generates a sequence \(\{x_n\}_{n=1}^{\infty}\) converging to \(x^*\) for any initial approximation \(x_0 \in [x^* - \delta, x^* + \delta]\).
Finding a Starting Point for Newton’s Method

Recall our initial argument that when $|x - x^*|$ is small, then $|x - x^*|^2 \ll |x - x^*|$, and we can neglect the second order term in the Taylor expansion.

In order for Newton’s method to converge we need a good starting point!

**Theorem**

Let $f(x) \in C^2[a, b]$. If $x^* \in [a, b]$ such that $f(x^*) = 0$ and $f'(x^*) \neq 0$, then there exists a $\delta > 0$ such that Newton’s method generates a sequence $\{x_n\}_{n=1}^{\infty}$ converging to $x^*$ for any initial approximation $x_0 \in [x^* - \delta, x^* + \delta]$.

The theorem is interesting, but quite useless for practical purposes. In practice: Pick a starting value $x_0$, iterate a few steps. Either the iterates converge quickly to the root, or it will be clear that convergence is unlikely.
Newton’s Method as a Fixed Point Iteration

If we view Newton’s method as a fixed point iteration...

\[
x_n = x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})}
\]

Then (the fixed point theorem), we must find an interval \([x^* - \delta, x^* + \delta]\) that \(g\) maps into itself, and for which \(|g'(x)| \leq k < 1\).
Newton’s Method as a Fixed Point Iteration

If we view Newton’s method as a fixed point iteration...

\[
x_n = x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})}
\]

Then (the fixed point theorem), we must find an interval \([x^* - \delta, x^* + \delta]\) that \(g\) maps into itself, and for which \(|g'(x)| \leq k < 1\). \(g'(x)\) is quite an expression:

\[
g'(x) = 1 - \frac{f'(x)f''(x) - f(x)f'''(x)}{[f'(x)]^2} = \frac{f(x)f''(x)}{[f'(x)]^2}
\]

By assumption, \(f(x^*) = 0\), \(f'(x^*) \neq 0\), so \(g'(x^*) = 0\). By continuity \(|g'(x)| \leq k < 1\) for some neighborhood of \(x^*\)... Hence the fixed point iteration will converge. (Gory details in the book).
Algorithm — Newton’s Method

**Algorithm: Newton’s Method**

**Input:** Initial approximation $p_0$; tolerance $TOL$; maximum number of iterations $N_0$.

**Output:** Approximate solution $p$, or failure message.

1. Set $i = 1$
2. While $i \leq N_0$ do 3--6
3. Set $p = p_0 - \frac{f(p_0)}{f'(p_0)}$
4. If $|p - p_0| < TOL$ then
   4a. output $p$
   4b. stop program
5. Set $i = i + 1$
6. Set $p_0 = p$
7. Output: “Failure after $N_0$ iterations.”
The main weakness of Newton’s method is the need to compute the derivative, $f'(\cdot)$, in each step. Many times $f'(\cdot)$ is far more difficult to compute and needs more arithmetic operations to calculate than $f(x)$.

What to do?? — **Approximate the derivative!**
The main weakness of Newton’s method is the need to compute the derivative, \( f'(\cdot) \), in each step. Many times \( f'(\cdot) \) is far more difficult to compute and needs more arithmetic operations to calculate than \( f(x) \).

What to do?? — **Approximate the derivative!**

By definition

\[
f'(x_{n-1}) = \lim_{x \to x_{n-1}} \frac{f(x) - f(x_{n-1})}{x - x_{n-1}}
\]

Let \( x = x_{n-2} \), and approximate

\[
f'(x_{n-1}) \approx \frac{f(x_{n-2}) - f(x_{n-1})}{x_{n-2} - x_{n-1}}.
\]
The Secant Method

Using the approximation

$$f'(x_{n-1}) \approx \frac{f(x_{n-2}) - f(x_{n-1})}{x_{n-2} - x_{n-1}}$$

for the derivative in Newton’s method

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

gives us the Secant Method

$$x_n = x_{n-1} - \frac{f(x_{n-1})}{f(x_{n-2}) - f(x_{n-1})} \left[ \frac{f(x_{n-2}) - f(x_{n-1})}{x_{n-2} - x_{n-1}} \right]$$

$$= x_{n-1} - \frac{f(x_{n-1}) [x_{n-2} - x_{n-1}]}{f(x_{n-2}) - f(x_{n-1})}$$
Strategy: The Secant Method

\[ x_n = x_{n-1} - \frac{f(x_{n-1}) [x_{n-2} - x_{n-1}]}{f(x_{n-2}) - f(x_{n-1})} \]

Instead of (as in Newton’s method) getting the next iterate from the zero-crossing of the tangent line, the next iterate for the secant method is the zero-crossing of the secant line...
Algorithm — The Secant Method

Algorithm: The Secant Method

Input: Initial approximations $p_0, p_1$; tolerance $TOL$; maximum number of iterations $N_0$.

Output: Approximate solution $p$, or failure message.

1. Set $i = 2$, $q_0 = f(p_0)$, $q_1 = f(p_1)$
2. While $i \leq N_0$ do 3--6
3. Set $p = p_1 - q_1 (p_1 - p_0)/(q_1 - q_0)$
4. If $|p - p_1| < TOL$ then
   4a. output $p$
   4b. stop program
5. Set $i = i + 1$
6. Set $p_0 = p_1$, $q_0 = q_1$, $p_1 = p$, $q_1 = f(p_1)$
7. Output: “Failure after $N_0$ iterations.”
Regula Falsi (the Method of False Position)

Regula Falsi is a combination of the Secant and the Bisection methods: We start with two points $a_{n-1}, b_{n-1}$ which bracket the root, *i.e.* $f(a_{n-1}) \cdot f(b_{n-1}) < 0$. Let $s_n$ be the zero-crossing of the secant-line, *i.e.*

$$s_n = b_{n-1} - f(b_{n-1}) \left[ \frac{a_{n-1} - b_{n-1}}{f(a_{n-1}) - f(b_{n-1})} \right].$$
Regula Falsi (the Method of False Position)

Regula Falsi is a combination of the Secant and the Bisection methods: We start with two points $a_{n-1}, b_{n-1}$ which bracket the root, i.e. $f(a_{n-1}) \cdot f(b_{n-1}) < 0$. Let $s_n$ be the zero-crossing of the secant-line, i.e.

$$s_n = b_{n-1} - f(b_{n-1}) \left[ \frac{a_{n-1} - b_{n-1}}{f(a_{n-1}) - f(b_{n-1})} \right].$$

Update as in the bisection method:

- if $f(a_{n-1}) \cdot f(s_n) > 0$ then $a_n = s_n, \quad b_n = b_{n-1}$
- if $f(a_{n-1}) \cdot f(s_n) < 0$ then $a_n = a_{n-1}, \quad b_n = s_n$

Regula Falsi is seldom used (it can run into some “issues” – to be explored soon), but illustrates how bracketing can be incorporated.
Algorithm — Regula Falsi

**Algorithm: Regula Falsi**

**Input:** Initial approximations \( p_0, p_1 \); tolerance \( TOL \); maximum number of iterations \( N_0 \).

**Output:** Approximate solution \( p \), or failure message.

1. Set \( i = 2, \quad q_0 = f(p_0), \quad q_1 = f(p_1) \)
2. While \( i \leq N_0 \) do 3--7
3. Set \( p = p_1 - q_1(p_1 - p_0)/(q_1 - q_0) \)
4. If \( |p - p_1| < TOL \) then
   4a. output \( p \)
   4b. stop program
5. Set \( i = i + 1, \quad q = f(p) \)
6. If \( q \cdot q_1 < 0 \) then set \( p_0 = p_1, \quad q_0 = q_1 \)
7. Set \( p_1 = p, \quad q_1 = q \)
8. Output: “Failure after \( N_0 \) iterations.”
<table>
<thead>
<tr>
<th>Method</th>
<th>Next Iterate</th>
</tr>
</thead>
</table>
| **Bisection**| Midpoint of bracketing interval: \( m_{n+1} = (a_n + b_n)/2 \):  
if \( f(c_{n+1})f(b_n) \leq 0 \), then \( \{a_{n+1} = m_{n+1}, \ b_{n+1} = b_n\} \)  
else \( \{a_{n+1} = a_n, \ b_{n+1} = m_{n+1}\} \). |
| **Regula Falsi** | Zero-crossing of secant line: \( s_{n+1} = x_n - f(x_n) \cdot \frac{x_n - x_{n-1}}{f(x_n) - f(x_{n-1})} \):  
if \( f(s_{n+1})f(b_n) < 0 \), then \( \{a_{n+1} = s_{n+1}, \ b_{n+1} = b_n\} \),  
else \( \{a_{n+1} = a_n, \ b_{n+1} = s_{n+1}\} \). |
| **Secant**   | Zero-crossing of secant line: \( x_{n+1} = x_n - f(x_n) \cdot \frac{x_n - x_{n-1}}{f(x_n) - f(x_{n-1})} \) |
| **Newton**   | Zero-crossing of tangent line: \( x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \) |
### Summary — Convergence

<table>
<thead>
<tr>
<th>Method</th>
<th>Convergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bisection</td>
<td><strong>Linear</strong> — Slow, each iteration gives 1 binary digit. We need about 3.3 iterations to gain one decimal digit...</td>
</tr>
<tr>
<td>Regula Falsi</td>
<td><strong>Linear</strong> — Faster than Bisection (ideally).</td>
</tr>
<tr>
<td>Secant</td>
<td><strong>Linear/Superlinear?</strong> — Slower than Newton.</td>
</tr>
<tr>
<td></td>
<td>Generally faster than Regula Falsi.</td>
</tr>
<tr>
<td></td>
<td>Burden-Faires says convergence rate is $\alpha \approx 1.62$.</td>
</tr>
<tr>
<td></td>
<td>After some digging around, I found a proof that the convergence rate should be $\frac{1+\sqrt{5}}{2}$, given sufficient smoothness of $f$, and $f'(x^*) \neq 0$.</td>
</tr>
<tr>
<td>Newton</td>
<td><strong>Quadratic.</strong> — In general. The fastest of the lot, when it works.</td>
</tr>
</tbody>
</table>
## Summary — Cost

<table>
<thead>
<tr>
<th>Method</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bisection</td>
<td>Each iteration is cheap — one function evaluation, one or two multiplications and one or two comparisons. Comparable to Regula Falsi.</td>
</tr>
<tr>
<td>Regula Falsi</td>
<td>Higher cost per iteration compared with Secant (conditional statements), Requires more iterations than Secant. Higher cost per iteration compared with Bisection, but requires fewer iterations.</td>
</tr>
<tr>
<td>Secant</td>
<td>Cheaper than Newton’s Method – no need to compute $f'(x)$. Slightly cheaper per iteration than Regula Falsi.</td>
</tr>
<tr>
<td>Newton</td>
<td>&quot;Expensive&quot; — We need to compute $f'(x)$ in every iteration.</td>
</tr>
</tbody>
</table>
## Summary — Comments

<table>
<thead>
<tr>
<th>Method</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bisection</td>
<td>Can be used to find a good starting interval for Newton’s method (if/when we have a problem finding a good starting point for Newton).</td>
</tr>
<tr>
<td>Regula Falsi</td>
<td>The combination of the Secant method and the Bisection method. All generated intervals bracket root (i.e. we carry a &quot;built-in&quot; error estimate at all times.)</td>
</tr>
<tr>
<td>Secant</td>
<td>Breaks down if $f(x_n) = f(x_{n-1})$ [division by zero]. Unknown basin of attraction (c.f. Newton’s method).</td>
</tr>
<tr>
<td>Newton</td>
<td>If $f'(x_k) = 0$ we’re in trouble. Works best when $</td>
</tr>
</tbody>
</table>
Newton’s Method and Friends — Things to Ponder...

- How to start
- How to update
- Can the scheme break?
  → Can we fix breakage? (How???)
- Relation to Fixed-Point Iteration

In the next section we will discuss the convergence in more detail.
Introduction: Error Analysis

In the previous section we discussed four different algorithms for finding the root of \( f(x) = 0 \).

We made some (sometime vague) arguments for why one method would be faster than another...

Now, we are going to look at the error analysis of iterative methods, and we will quantify the speed of our methods.

**Note:** The discussion may be a little “dry,” but do not despair! In the “old days” before fancy-schmancy computers were commonplace it was almost true that numerical analysis \( \equiv \) error analysis, here we only look at some basics...
Definition of Convergence for a Sequence

**Definition**

Suppose the sequence \( \{p_n\}_{n=0}^{\infty} \) converges to \( p \), with \( p_n \neq p \) for all \( n \). If positive constants \( \lambda \) and \( \alpha \) exists with

\[
\lim_{n \to \infty} \frac{|p_{n+1} - p|}{|p_n - p|^\alpha} = \lambda
\]

then \( \{p_n\}_{n=0}^{\infty} \) converges to \( p \) of order \( \alpha \), with asymptotic error constant \( \lambda \).

An iterative technique of the form \( p_n = g(p_{n-1}) \) is said to be of order \( \alpha \) if the sequence \( \{p_n\}_{n=0}^{\infty} \) converges to the solution \( p = g(p) \) of order \( \alpha \).

**Bottom line:** High order (\( \alpha \)) \( \Rightarrow \) Faster convergence (more desirable).

\( \lambda \) has an effect, but is less important than the order.
Special Cases: $\alpha = 1$, and $\alpha = 2$

When $\alpha = 1$ the sequence is **linearly convergent**.

When $\alpha = 2$ the sequence is **quadratically convergent**.

When $\alpha < 1$ the sequence is **sub-linearly convergent** (very undesirable, or “painfully slow.”)

When $((\alpha = 1 \text{ and } \lambda = 0) \text{ or } 1 < \alpha < 2)$, the sequence is **super-linearly convergent**.
Suppose we have two sequences converging to zero:

\[
\lim_{n \to \infty} \frac{|p_{n+1}|}{|p_n|} = \lambda_p, \quad \lim_{n \to \infty} \frac{|q_{n+1}|}{|q_n|^2} = \lambda_q
\]

Roughly this means that

\[
|p_n| \approx \lambda_p |p_{n-1}| \approx \lambda_p^n |p_0|, \quad |q_n| \approx \lambda_q |q_{n-1}|^2 \approx \lambda_q^{2^n-1} |q_0|^{2^n}
\]
Now, assume $\lambda_p = \lambda_q = 0.9$ and $p_0 = q_0 = 1$, we get the following

<table>
<thead>
<tr>
<th>n</th>
<th>$p_n$</th>
<th>$q_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>0.81</td>
<td>0.729</td>
</tr>
<tr>
<td>3</td>
<td>0.729</td>
<td>0.4782969</td>
</tr>
<tr>
<td>4</td>
<td>0.6561</td>
<td>0.205891132094649</td>
</tr>
<tr>
<td>5</td>
<td>0.59049</td>
<td>0.0381520424476946</td>
</tr>
<tr>
<td>6</td>
<td>0.531441</td>
<td>0.00131002050863762</td>
</tr>
<tr>
<td>7</td>
<td>0.4782969</td>
<td>0.00000154453835975</td>
</tr>
<tr>
<td>8</td>
<td>0.43046721</td>
<td>0.000000000000021470</td>
</tr>
</tbody>
</table>

**Table (Linear vs. Quadratic):** A dramatic difference! After 8 iterations, $q_n$ has 11 correct decimals, and $p_n$ still *none*. $q_n$ roughly doubles the number of correct digits in every iteration. Here $p_n$ needs more than 20 iterations/digit-of-correction.
Let \( g \in C[a, b] \) be such that \( g(x) \in [a, b] \) for all \( x \in [a, b] \). Suppose, in addition that \( g'(x) \) is continuous on \((a, b)\) and there is a positive constant \( k < 1 \) so that

\[
|g'(k)| \leq k, \quad \forall x \in (a, b)
\]

If \( g'(p^*) \neq 0 \), then for any number \( p_0 \) in \([a, b]\), the sequence

\[
p_n = g(p_{n-1}), \quad n \geq 1
\]

converges only linearly to the unique fixed point \( p^* \) in \([a, b]\).

In a sense, this is bad news since we like fast convergence...
Convergence of General Fixed Point Iteration

The existence and uniqueness of the fixed point follows from the fixed point theorem.

We use the mean value theorem to write

\[ p_{n+1} - p^* = g(p_n) - g(p^*) = g'(\xi_n)(p_n - p^*), \quad \xi_n \in (p_n, p^*) \]
Convergence of General Fixed Point Iteration

Proof

The existence and uniqueness of the fixed point follows from the fixed point theorem.

We use the mean value theorem to write

\[ p_{n+1} - p^* = g(p_n) - g(p^*) = g'(\xi_n)(p_n - p^*), \quad \xi_n \in (p_n, p^*) \]

Since \( p_n \to p^* \) and \( \xi_n \) is between \( p_n \) and \( p^* \), we must also have \( \xi_n \to p^* \).

Further, since \( g'(\cdot) \) is continuous, we have

\[ \lim_{n \to \infty} g'(\xi_n) = g'(p^*) \]
The existence and uniqueness of the fixed point follows from the fixed point theorem.

We use the mean value theorem to write

\[ p_{n+1} - p^* = g(p_n) - g(p^*) = g'(\xi_n)(p_n - p^*), \quad \xi_n \in (p_n, p^*) \]

Since \( p_n \to p^* \) and \( \xi_n \) is between \( p_n \) and \( p^* \), we must also have \( \xi_n \to p^* \). Further, since \( g'(\cdot) \) is continuous, we have

\[ \lim_{n \to \infty} g'(\xi_n) = g'(p^*) \]

Thus,

\[ \lim_{n \to \infty} \left| \frac{p_{n+1} - p^*}{p_n - p^*} \right| = \lim_{n \to \infty} |g'(\xi_n)| = |g'(p^*)| \]

So if \( g'(p^*) \neq 0 \), the fixed point iteration converges linearly with asymptotic error constant \( |g'(p^*)| \).
**Bottom Line:** The theorem tells us that if we are looking to design rapidly converging fixed point schemes, we must design them so that $g'(p^*) = 0$...
**Bottom Line:** The theorem tells us that if we are looking to design rapidly converging fixed point schemes, we must design them so that \( g'(p^*) = 0 \).

We state the following without proof:

**Theorem**

Let \( p^* \) be a solution of \( p = g(p) \). Suppose \( g'(p^*) = 0 \), and \( g''(x) \) is continuous and strictly bounded by \( M \) on an open interval \( I \) containing \( p^* \). Then there exists a \( \delta > 0 \) such that, for \( p_0 \in [p^* - \delta, p^* + \delta] \) the sequence defined by \( p_n = g(p_{n-1}) \) converges at least quadratically to \( p^* \). Moreover, for sufficiently large \( n \)

\[
|p_{n+1} - p^*| < \frac{M}{2} |p_n - p^*|^2
\]
Practical Application of the Theorems

The theorems tell us:

“Look for quadratically convergent fixed point methods among functions whose derivative is zero at the fixed point.”

We want to solve: \( f(x) = 0 \) using fixed point iteration. We write the problem as an equivalent fixed point problem:

\[
g(x) = x - f(x) \quad \text{Solve: } x = g(x)\\
g(x) = x - \alpha f(x) \quad \text{Solve: } x = g(x) \quad \alpha \text{ a constant}\\
g(x) = x - \Phi(x)f(x) \quad \text{Solve: } x = g(x) \quad \Phi(x) \text{ differentiable}
\]

We use the most general form (the last one).

Remember, we want \( g'(p^*) = 0 \) when \( f(p^*) = 0 \).
Practical Application of the Theorems... Newton’s Method Rediscovered

\[ g'(x) = \frac{d}{dx} [x - \Phi(x)f(x)] = 1 - \Phi'(x)f(x) - \Phi(x)f'(x) \]

at \( x = p^* \) we have \( f(p^*) = 0 \), so

\[ g'(p^*) = 1 - \Phi(p^*)f'(p^*). \]
Practical Application of the Theorems... Newton’s Method Rediscovered

\[ g'(x) = \frac{d}{dx} [x - \Phi(x)f(x)] = 1 - \Phi'(x)f(x) - \Phi(x)f'(x) \]

at \( x = p^* \) we have \( f(p^*) = 0 \), so

\[ g'(p^*) = 1 - \Phi(p^*)f'(p^*). \]

For quadratic convergence we want this to be zero, that’s true if

\[ \Phi(p^*) = \frac{1}{f'(p^*)}. \]
Practical Application of the Theorems... Newton’s Method Rediscovered

\[ g'(x) = \frac{d}{dx} [x - \Phi(x)f(x)] = 1 - \Phi'(x)f(x) - \Phi(x)f'(x) \]

at \( x = p^* \) we have \( f(p^*) = 0 \), so

\[ g'(p^*) = 1 - \Phi(p^*)f'(p^*). \]

For quadratic convergence we want this to be zero, that’s true if

\[ \Phi(p^*) = \frac{1}{f'(p^*)}. \]

Hence, our scheme is

\[ g(x) = x - \frac{f(x)}{f'(x)}, \quad \text{Newton’s Method, rediscovered!} \]
Newton’s Method

We have “discovered” Newton’s method in two scenarios:

1. From formal Taylor expansion.
2. From convergence optimization of Fixed point iteration.

It is clear that we would like to use Newton’s method in many settings. One major problem is that it breaks when $f'(p^*) = 0$ (division by zero).

The good news is that this problem can be fixed! — We need a short discussion on the multiplicity of zeroes.
Definition: Multiplicity of a Root

A solution $p^*$ of $f(x) = 0$ is a zero of multiplicity $m$ of $f$ if for $x \neq p$ we can write

$$f(x) = (x - p^*)^m q(x), \quad \lim_{x \to p^*} q(x) \neq 0$$

Basically, $q(x)$ is the part of $f(x)$ which does not contribute to the zero of $f(x)$.

If $m = 1$ then we say that $f(x)$ has a simple zero.

Theorem

$f \in C^1[a, b]$ has a simple zero at $p^*$ in $(a, b)$ if and only if $f(p^*) = 0$, but $f'(p^*) \neq 0$. 
Theorem (Multiplicity and Derivatives)

The function \( f \in C^m[a, b] \) has a zero of multiplicity \( m \) at \( p^* \) in \((a, b)\) if and only if

\[
0 = f(p^*) = f'(p^*) = \cdots f^{(m-1)}(p^*), \quad \text{but } f^{(m)}(p^*) \neq 0.
\]

We know that Newton’s method runs into trouble when we have a zero of multiplicity higher than 1.
Newton’s Method for Zeroes of Higher Multiplicity

Suppose $f(x)$ has a zero of multiplicity $m > 1$ at $p^*$...

Define the new function

$$
\mu(x) = \frac{f(x)}{f'(x)}.
$$
Newton’s Method for Zeroes of Higher Multiplicity

Suppose \( f(x) \) has a zero of multiplicity \( m > 1 \) at \( p^* \)...

Define the new function

\[
\mu(x) = \frac{f(x)}{f'(x)}.
\]

We can write \( f(x) = (x - p^*)^m q(x) \), hence

\[
\mu(x) = \frac{(x - p^*)^m q(x)}{m(x - p^*)^{m-1} q(x) + (x - p^*)^m q'(x)}
\]

\[
= (x - p^*) \frac{q(x)}{mq(x) + (x - p^*)q'(x)}
\]
Suppose \( f(x) \) has a zero of multiplicity \( m > 1 \) at \( p^* \)...

Define the new function

\[
\mu(x) = \frac{f(x)}{f'(x)}.
\]

We can write \( f(x) = (x - p^*)^m q(x) \), hence

\[
\mu(x) = \frac{(x - p^*)^m q(x)}{m(x - p^*)^{m-1} q(x) + (x - p^*)^m q'(x)}
\]

\[
= (x - p^*) \frac{q(x)}{m q(x) + (x - p^*)q'(x)}
\]

This expression has a simple zero at \( p^* \), since

\[
\frac{q(p^*)}{m q(p^*) + (p^* - p^*) q'(p^*)} = \frac{1}{m} \neq 0
\]
Now we apply Newton’s method to $\mu(x)$:

$$x = g(x) = x - \frac{\mu(x)}{\mu'(x)}$$

$$= x - \frac{f'(x)}{[f'(x)]^2 - f(x)f''(x)}$$

$$= x - \frac{f(x)f'(x)}{[f'(x)]^2 - f(x)f''(x)}$$

This iteration will converge quadratically!
Strategy: “Fixed Newton” (for Zeroes of Multiplicity $\geq 2$)

$$x_{n+1} = x_n - \frac{f(x_n)f'(x_n)}{[f'(x_n)]^2 - f(x_n)f''(x_n)}$$

**Drawbacks:**
We have to compute $f''(x)$ — more expensive and possibly another source of numerical and/or measurement errors.

We have to compute a more complicated expression in each iteration — more expensive.

Roundoff errors in the denominator — both $f'(x)$ and $f(x)$ approach zero, so we are computing the difference between two small numbers; a serious cancelation risk.