Fixed Point Iteration

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Fixed Point

intersections of $y = x$ and $y = g(x)$.

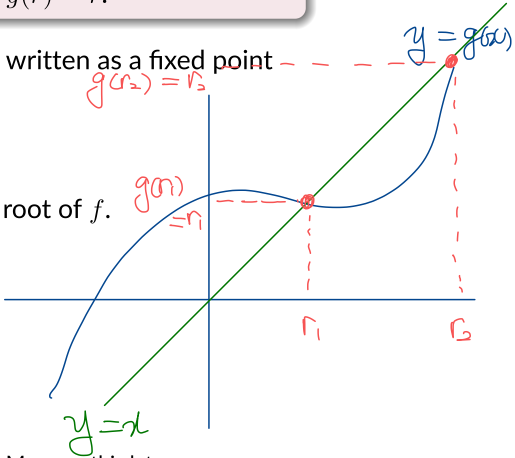
Definition 1 (Fixed Point)

The real number r is a **fixed point** of the function g if $g(r) = r$.

- The rootfinding problem $f(x) = 0$ can always be written as a fixed point problem $g(x) = x$ by, *e.g.*, setting[1]

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

- The fixed point problem is true at, and only at, a root of f.



"(fixed point of g) = (root of f)"

$g(r) = r - f(r) = r$

$\Rightarrow \cancel{r} - f(r) = \cancel{r} \Rightarrow f(r) = 0.$

[1] This is not the only way to transform the rootfinding problem. More on this later.

Fixed Point Iteration

A fixed point problem $g(x) = x$ naturally provides an iteration scheme:

$$\begin{cases} x_0 = \text{initial guess} \\ x_{k+1} = g(x_k), \quad k = 0, 1, 2, \ldots. \end{cases} \qquad \text{(fixed point iteration)}$$

x_0

$x_1 = g(x_0)$

$x_2 = g(x_1)$

$x_3 = g(x_2)$

$\vdots$

- The sequence $\{x_k\}$ may or may not converge as $k \to \infty$.
- If g is continuous and $\{x_k\}$ converges to a number r, then r is a fixed point of g.

means $g(r) = r$.

$$g(r) = g\left(\lim_{k\to\infty} x_k\right) = \lim_{k\to\infty} g(x_k) = \lim_{k\to\infty} x_{k+1} = r.$$

- $\lim_{k\to\infty} x_k = r$
- $\lim_{k\to\infty} x_{k+1} = r$

because g is continuous.

Fixed Point Iteration Algorithm

```
function x = fpi(g, x0, n)
% FPI x = fpi(g, x0, n)
% Computes approximate solution of g(x)=x
% Input:
%   g    function handle
%   x0   initial guess
%   n    number of iteration steps
    x = x0;
    for k = 1:n
        x = g(x);  ← repeated overwrite.
    end
end
```

Examples

initial iterate x_0.

- To find a fixed point of $g(x) = 0.3\cos(2x)$ near 0.5 using `fpi`:

```
g = @(x) 0.3*cos(2*x);
xc = fpi(g,0.5,20)
```

```
xc = 0.260266319627758
```

Not All Fixed Point Problems Are The Same

$g(x) = \underbrace{x - f(x) = x}$

$f(x) = 0$

The rootfinding problem $f(x) = x^3 + x - 1 = 0$ can be transformed to various fixed point problems:

- $g_1(x) = x - f(x) = 1 - x^3$
- $g_2(x) = \sqrt[3]{1-x}$
- $g_3(x) = \dfrac{1+2x^3}{1+3x^2}$

$g_2(x) = x$

$\sqrt[3]{1-x} = x$

$1 - x = x^3$

$0 = \underline{x^3 + x - 1 = f(x)}$

$g_3(x) = x$

$\dfrac{1+2x^3}{1+3x^2} = x$

$1 + 2x^3 = x(1+3x^2)$

$= x + 3x^3$

$0 = x^3 + x - 1$

$\parallel$

$f(x)$

Note that all $g_j(x) = x$ are equivalent to $f(x) = 0$. However, not all these find a fixed point of g, that is, a root of f on the computer.

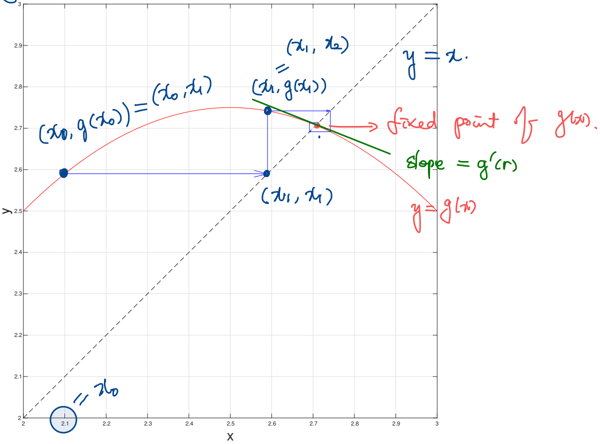
Exercise. Run `fpi` with g_j and $x_0 = 0.5$. Which fixed point iterations converge?

Geometry of Fixed Point Iteration

The following script[2] finds a root of $f(x) = x^2 - 4x + 3.5$ via FPI.

$$g(x) = x - f(x) = x - (x^2 - 4x + 3.5) = -x^2 + 5x - 3.5$$

```
f = @(x) x.^2 - 4*x + 3.5;
g = @(x) x - f(x);
fplot(g, [2 3], 'r');
hold on
plot([2 3], [2 3], 'k--')
x = 2.1;
y = g(x);
for k = 1:5
    arrow([x y], [y y], 'b');
    x = y; y = g(x);
    arrow([x x], [x y], 'b');
end
```



Note the line segments spiral in towards the fixed point.

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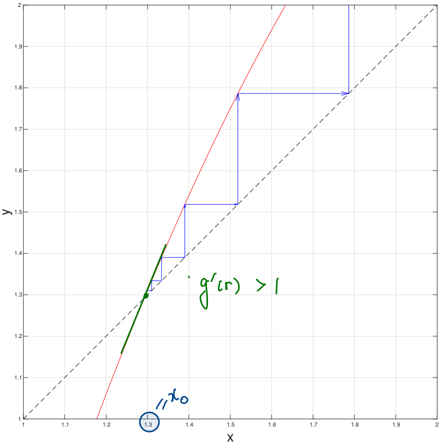
[2] Modified from FNC.

Geometry of Fixed Point Iteration (cont')

However, with a different starting point, the process does not converge.

```
clf
fplot(g, [1 2], 'r');
hold on
plot([1 2], [1 2], 'k--'),
ylim([1 2])
x = 1.3; y = g(x);
for k = 1:5
    arrow([x y], [y y], 'b');
    x = y; y = g(x);
    arrow([x x], [x y], 'b');
end
```



Custom function: `arrow = @(p1, p2, varargin) quiver(p1(1), p1(2), p2(1)-p1(1), p2(2)-p1(2), 0, varargin{:})`

Series Analysis

(Taylor series)

Context $\begin{cases} x_0 \text{ initial iter.} \\ x_{k+1} = g(x_k) \end{cases}$; $\lim_{k\to\infty} x_k = r \leftarrow$ fixed point of g.

Let $\epsilon_k = x_k - r$ be the sequence of errors.

$x_k = r + \epsilon_k$; $\lim_{k\to\infty} \epsilon_k = 0$ because $\lim_{k\to\infty} x_k = r$.

- The iteration formula $x_{k+1} = g(x_k)$ can be written as

$$\epsilon_{k+1} + \cancel{r} = g(\epsilon_k + r)$$
$$= \underbrace{g(r)}_{= \cancel{r}} + g'(r)\epsilon_k + \frac{1}{2}g''(r)\epsilon_k^2 + \cdots, \qquad \text{(Taylor series)}$$

implying

$$\epsilon_{k+1} = g'(r)\epsilon_k + O(\epsilon_k^2)$$

assuming sufficient regularity of g.

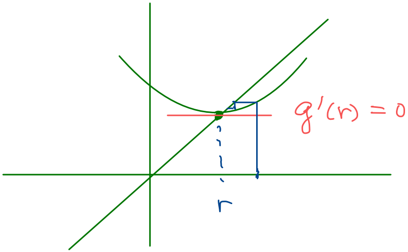
- Neglecting the second-order term, we have $\epsilon_{k+1} \approx g'(r)\epsilon_k$, which is satisfied if $\epsilon_k \approx C\left[g'(r)\right]^k$ for sufficiently large k. (geometric sequence)
- Therefore, the iteration converges if $|g'(r)| < 1$ and diverges if $|g'(r)| > 1$.

Sanity check: $\epsilon_{k+1} \approx C[g'(r)]^{k+1} = g'(r)\, C[g'(r)]^k \approx g'(r)\,\epsilon_k$ ✓

Upshot

If the fixed point iterates $\{x_k\}$ of g converges to r, then

$$\epsilon_{k+1} \approx g'(r)\,\epsilon_k \quad \text{with} \quad |g'(r)| < 1.$$



$$\frac{\epsilon_{k+1}}{\epsilon_k} \approx g'(r)$$

Note: Rate of Convergence

$$\frac{\epsilon_{n+1}}{\epsilon_n^{\,3}} \approx \star$$

Definition 2 (Linear Convergnece)

Suppose $\lim_{k\to\infty} x_k = r$ and let $\epsilon_k = x_k - r$, the error at step k of an iteration method. If

$$\lim_{k\to\infty} \frac{|\epsilon_{k+1}|}{|\epsilon_k|} = \sigma < 1,$$

the method is said to obey **linear convergence** with rate σ.

Note. In general, say

$$\lim_{k\to\infty} \frac{|\epsilon_{k+1}|}{|\epsilon_k|^p} = \sigma$$

for some $p \geqslant 1$ and $\sigma > 0$.

- If $p = 1$ and
  - $\sigma = 1$, the convergence is *sublinear*; slower
  - $0 < \sigma < 1$, the convergence is *linear*;
  - $\sigma = 0$, the convergence is *superlinear*. faster
- If $p = 2$, the convergence is *quadratic*;
- If $p = 3$, the convergence is *cubic*, ...

Convergence of Fixed Point Iteration

g is diff'ble and g' is cts.

Theorem 3 (Convergence of FPI)

Assume that g is continuously differentiable, that $g(r) = r$, and that $\sigma = |g'(r)| < 1$. Then the fixed point iterates x_k generated by

$$x_{k+1} = g(x_k), \quad k = 1, 2, \ldots,$$

converge linearly with rate σ to the fixed point r for x_0 sufficiently close to r.

In the previous example with $g(x) = x - f(x) = -x^2 + 5x - 3.5$:

- For the first fixed point, near 2.71, we get $g'(r) \approx -0.42$ (convergence);
- For the second fixed point, near 1.29, we get $g'(r) \approx 2.42$ (divergence).

Note. An iterative method is called **locally convergent** to r if the method converges to r for initial guess sufficiently close to r.

Contraction Maps

Lipschitz Condition

A function g is said to satisfy a **Lipschitz condition** with constant L on the interval $S \subset \mathbb{R}$ if

$$\left|g(s) - g(t)\right| \leqslant L\,|s - t| \quad \text{for all } s, t \in S.$$

- A function satisfying the Lipschitz condition is continuous on S.
- If $L < 1$, g is called a **contraction map**.

When Does FPI Succeed?

Contraction Mapping Theorem

Suppose that g satisfies Lipschitz condition on S with $L < 1$, *i.e.*, g is a contraction map on S. Then S contains exactly one fixed point r of g. If $x_1, x_2, \ldots$ are generated by the fixed point iteration $x_{k+1} = g(x_k)$, and $x_1, x_2, \ldots$ all lie in S, then

$$|x_k - r| \leqslant L^{k-1} |x_1 - r|, \quad k > 1.$$