Polynomial Approximation and Sequences

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Part I
Polynomial Approximation

Keywords. Taylor's Theorem, Taylor polynomial, error / remainder term, Cauchy, Lagrange, integral form.

Theorem 1 (Taylor's Theorem)**.** *If $f',\dots,f^{(n+1)}$ are defined on $[a,x]$, then*

$$f(x)=f(a)+f'(a)(x-a)+\cdots+\frac{f^{(n)}(a)}{n!}(x-a)^n+R_n(x)$$

where $R_n(x)=\frac{f^{(n+1)}(t)}{(n+1)!}(x-a)^{n+1}$ for some t in (a,x).

Note 2. The Mean Value Theorem is a special case of Taylor's Theorem:

$$f(b)=f(a)+f'(c)(b-a)$$

for some c between a and b.

Part II
Sequences

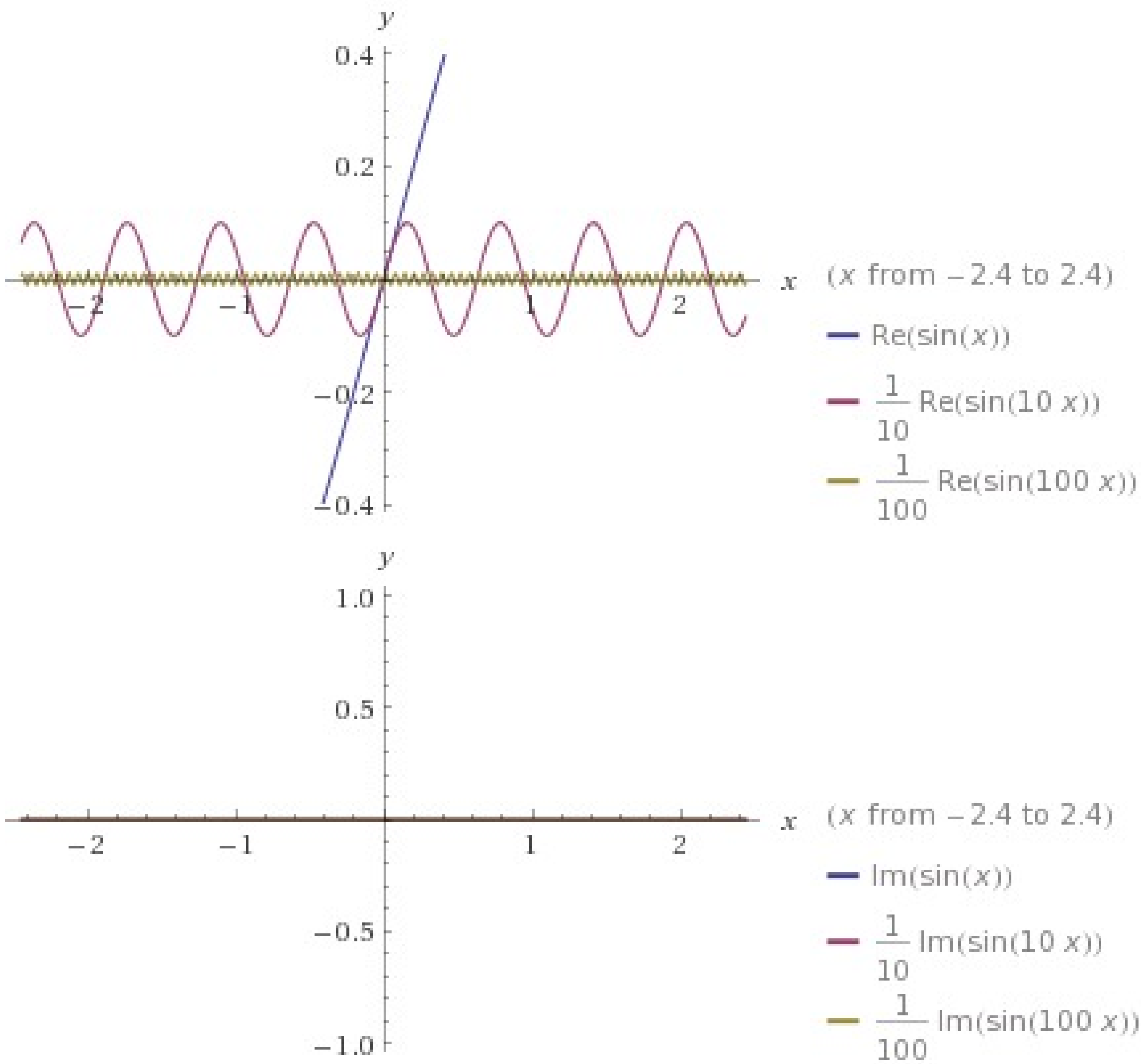
Keywords. Point-wise, uniform convergence, metric space, Cauchy criterion, Koch snowflake, Weierstrass function, uniformly distributed / equidistributed sequence.

Theorem 3 (Uniform Limit Theorem)**.** *Uniform convergence of functions preserves continuity, i.e. if f_n are continuous and approach f uniformly, then f is continuous.*

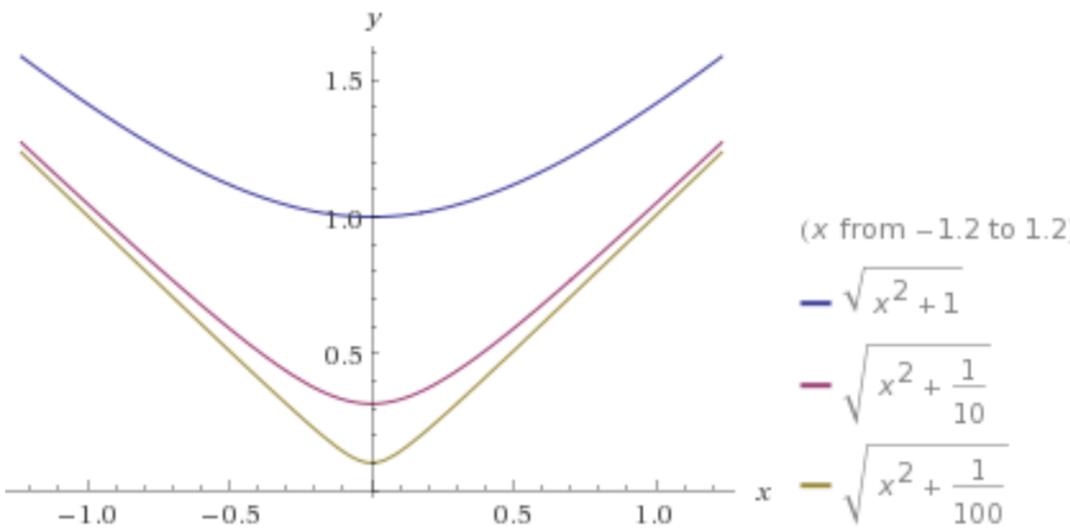
Proposition 4. *The uniform limit of uniformly continuous functions is uniformly continuous.*

Question 5. *What about differentiability, i.e. if f_n are differentiable and approach f uniformly, is f always differentiable, and is* $\lim f_n' = f'$*?*

Example 6. No to the second question: the functions $f_n(x) = \frac{1}{n}\sin(nx)$ converge uniformly to the zero function, which *is* differentiable. But, the limit of the derivatives don't exist. What about just differentiability?



Example 7. Still No, e.g. the functions $f_n(x) = \sqrt{x^2 + 1/n}$ converge uniformly to $f = |x|$, which is not differentiable at zero.



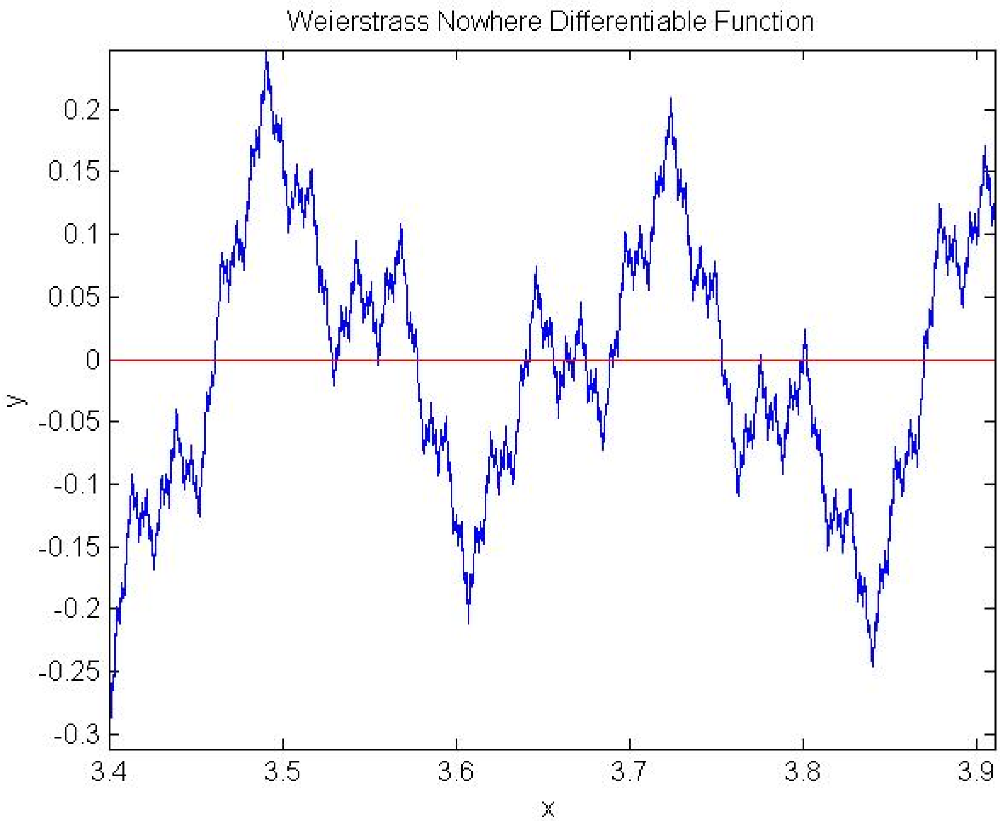
Example 8 (Weierstrass function)**.** The Weierstrass function

$$f(x) = \sum_{k=0}^{\infty} a^k \cos(b^k \pi x),$$

for appropriate values a and b, is the uniform limit of

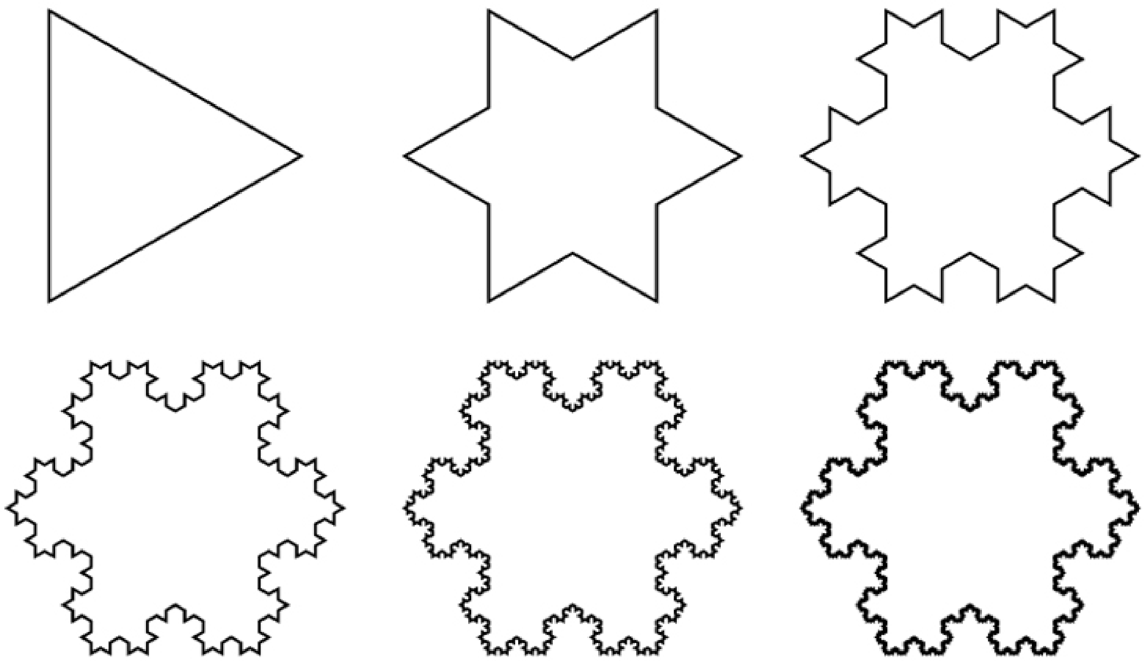
$$f_n = \sum_{k=0}^{n} a^k \cos(b^k \pi x),$$

but is nowhere differentiable.



Question 9. *Is the Koch snowflake nowhere differentiable?*

Yes. Proof?



Definition 10. Let $\{a_n\}$ be a sequence, and $0 \le a < b \le 1$. Let $N(n;a,b)$ be the number of integers $j \le n$ s.t. $a_j \in [a,b]$. A sequence $\{a_n\}$ of numbers in $[0,1]$ is called uniformly distributed in $[0,1]$ if

$$\lim_{n\to\infty} \frac{N(n;a,b)}{n} = b-a$$

for all a,b, s.t. $0 \le a < b \le 1$.

Proposition 11. *If s is a step function on $[0,1]$, and $\{a_n\}$ is uniformly distributed in $[0,1]$, then*

$$\int_0^1 s = \lim_{n\to\infty} \frac{s(a_1)+\cdots+s(a_n)}{n}.$$

Proof. Let $\Delta_1,\ldots,\Delta_m$ be a partition of $[0,1]$ corresponding to the steps in s. Then (with a slight abuse of notation) we have

$$\begin{aligned}\int_0^1 s &= \sum_{i=1}^m s(\Delta_i)\Delta_i \\ &= \sum_{i=1}^m s(\Delta_i) \lim_{n\to\infty} \frac{1}{n} N(n;\Delta_i) \\ &= \lim_{n\to\infty} \frac{1}{n} \sum_{i=1}^m s(\Delta_i) N(n;\Delta_i) \\ &= \lim_{n\to\infty} \frac{1}{n} \sum_{i=1}^n s(a_i). \end{aligned}$$ □

Proposition 12. *If f is integrable on $[0,1]$, and $\{a_n\}$ is uniformly distributed in $[0,1]$, then*

$$\int_0^1 f = \lim_{n\to\infty} \frac{f(a_1)+\cdots+f(a_n)}{n}.$$

Sketch. Since f is integrable, there is a step function s such that $\int_0^1 f$ is close to $\int_0^1 s$, which is close to $\frac{s(a_1)+\cdots+s(a_n)}{n}$, which is close to $\frac{f(a_1)+\cdots+f(a_n)}{n}$. □