19. Taylor Polynomials

If $f\colon A \longrightarrow \mathbb{R}^m$ is a differentiable function, and we are given a point $P \in A$, one can use the derivative to write down the best linear approximation to f at P. It is natural to wonder if one can do better using quadratic, or even higher degree, polynomials. We start with the one dimensional case.

Definition 19.1. *Let $I \subset \mathbb{R}$ be an open interval and let $f\colon I \longrightarrow \mathbb{R}$ be a $\mathcal{C}^k$-function. Given a point $a \in I$, let*

$$\begin{aligned} P_{a,k}f(x) &= f(a) + f'(a)(x-a) + \frac{f''(a)}{2}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \cdots + \frac{f^k(a)}{k!}(x-a)^k \\ &= \sum_{i=0}^{k} \frac{f^i(a)}{i!}(x-a)^i. \end{aligned}$$

Then $P_{a,k}f(x)$ is the kth ***Taylor polynomial of*** *f, centred at a. The* ***remainder*** *is the difference*

$$R_{a,k}f(x) = f(x) - P_{a,k}f(x).$$

Note that we have chosen $P_{a,k}f$ so that the first k derivatives of $P_{a,k}f$ at a are precisely the same as those of f. In other words, the first k derivatives at a of the remainder are all zero. The remainder is a measure of how good the Taylor polynomial approximates $f(x)$ and so it is very useful to estimate $R_{a,k}(x)$.

Theorem 19.2 (Taylor's Theorem with remainder)**.** *Let $I \subset \mathbb{R}$ be an open interval and let $f\colon I \longrightarrow \mathbb{R}$ be a $\mathcal{C}^{k+1}$-function. Let a and b be two points in I.*

Then there is a ξ between a and b, such that

$$R_{a,k}f(b) = \frac{f^{k+1}(\xi)}{(k+1)!}(b-a)^{k+1}.$$

Proof. If $a = b$ then take $\xi = a$. The result is clear in this case. Otherwise if we put

$$M = \frac{R_{a,k}f(b)}{(b-a)^{k+1}},$$

then

$$R_{a,k}f(b) = M(b-a)^{k+1}.$$

We want to show that there is some ξ between a and b such that

$$M = \frac{f^{k+1}(\xi)}{(k+1)!}.$$

If we let

$$g(x) = R_{a,k}(x) - M(x-a)^{k+1},$$

then

$$g^{k+1}(x) = f^{k+1}(x) - k!M.$$

Then we are looking for ξ such that

$$g^{k+1}(\xi) = 0.$$

Now the first k derivatives of g at a are all zero,

$$g^i(a) = 0 \qquad \text{for} \qquad 0 \leq i \leq k.$$

By choice of M,

$$g(b) = 0.$$

So by the mean value theorem, applied to $g(x)$, there is a ξ_1 between a and b such that

$$g'(\xi_1) = 0.$$

Again by the mean value theorem, applied to $g'(x)$, there is a ξ_2 between a and ξ_1 such that

$$g''(\xi_2) = 0.$$

Continuing in this way, by induction we may find ξ_i, $1 \leq i \leq k+1$ between a and ξ_{i-1} such that

$$g^i(\xi_i) = 0.$$

Let $\xi = \xi_{k+1}$. $\square$

Let's try an easy example. Start with

$$\begin{aligned}
f(x) &= x^{1/2} \\
f'(x) &= \frac{1}{2}x^{-1/2} \\
f''(x) &= \frac{1}{2^2}x^{-3/2} \\
f'''(x) &= \frac{3}{2^3}x^{-5/2} \\
f^4(x) &= -\frac{1\cdot 3\cdot 5}{2^4}x^{-7/2} \\
f^5(x) &= \frac{1\cdot 3\cdot 5\cdot 7}{2^5}x^{-9/2} \\
f^6(x) &= -\frac{1\cdot 3\cdot 5\cdot 7\cdot 9}{2^6}x^{-11/2} \\
f^k(x) &= (-1)^{k-1}\frac{(2k-1)!!}{2^k}x^{-(2k-1)/2} \\
f^k(9/4) &= (-1)^{k-1}\frac{(2k-1)!!}{2^k}\frac{2^{2k-1}}{3^{2k-1}} \\
&= (-1)^{k-1}\frac{(2k-1)!!2^{k-1}}{3^{2k-1}}.
\end{aligned}$$

Let's write down the Taylor polynomial centred at $a = 9/4$.

$$\begin{aligned}
P_{9/4,5}f(x) = f(9/4)+f'(9/4)(x-9/4)+f''(9/4)/2(x-9/4)^2+f'''(9/4)/6(x-9/4)^3 \\
f^4(9/4)/24(x-9/4)^4+f^5(9/4)/120(x-9/4)^5.
\end{aligned}$$

So,

$$\begin{aligned}
P_{9/4,5}f(x) &= 3/2+1/3(x-9/4)-1/3^3(x-9/4)^2+2/3^5(x-9/4)^3 \\
&\quad -\frac{1\cdot 3\cdot 5\cdot 2^3}{24\cdot 3^7}(x-9/4)^4+\frac{1\cdot 3\cdot 5\cdot 7\cdot 2^4}{120\cdot 3^9}(x-9/4)^5.
\end{aligned}$$

If we plug in $x = 2$, so that $x - 9/4 = -1/4$ we get an approximation to $f(2) = \sqrt{2}$.

$$P_{9/4,3}(2) = 3/2+1/3(-1/4)-1/3^3(1/4)^2-2/3^5(1/4)^3 = \frac{10997}{7776} \approx 1.41422\ldots.$$

On the other hand,

$$|R_3(2,9/4)| = \frac{1\cdot 3}{4!}(\xi)^{-7/2}(1/4)^4 < \frac{1\cdot 3}{4!}(1/2) = 1/16.$$

In fact

$$|R_3(2,9/4)| = \frac{10997}{7776} - \sqrt{2} \approx 4\times 10^{-6}.$$

Definition 19.3. *Let $A \subset \mathbb{R}^n$ be an open subset which is convex (if $\vec{a}$ and $\vec{b}$ belong to A, then so does every point on the line segment between them). Suppose that $f\colon A \longrightarrow \mathbb{R}$ is $\mathcal{C}^k$.*

Given $\vec{a} \in A$, the kth ***Taylor polynomial*** *of f centred at a is*

$$P_{\vec{a},k}f(\vec{x}) = f(\vec{a}) + \sum_{1\leq i\leq n} \frac{\partial f}{\partial x_i}(\vec{a})(x_i - a_i) + 1/2 \sum_{1\leq i,j\leq n} \frac{\partial^2 f}{\partial x_i \partial x_j}(\vec{a})(x_i - a_i)(x_j - a_j) + \dots$$

$$+ \frac{1}{k!} \sum_{1\leq i_1,i_2,\dots,i_k\leq n} \frac{\partial^k f}{\partial x_{i_1}\partial x_{i_2}\dots\partial x_{i_k}}(\vec{a})(x_{i_1} - a_{i_1})(x_{i_2} - a_{i_2})\dots(x_{i_k} - a_{i_k}).$$

The ***remainder*** *is the difference*

$$R_{\vec{a},k}f(\vec{x}) = f(\vec{x}) - P_{\vec{a},k}f(\vec{x}).$$

Theorem 19.4. *Let $A \subset \mathbb{R}^n$ be an open subset which is convex. Suppose that $f\colon A \longrightarrow \mathbb{R}$ is $\mathcal{C}^{k+1}$, and let $\vec{a}$ and $\vec{b}$ belong to A.*

Then there is a vector $\vec{\xi}$ on the line segment between $\vec{a}$ and $\vec{b}$ such that

$$R_{\vec{a},k}(\vec{b}) = \frac{1}{(k+1)!} \sum_{1\leq l_1,l_2,\dots,l_{k+1}\leq n} \frac{\partial^{k+1} f}{\partial x_{i_1}\partial x_{i_2}\dots\partial x_{i_{k+1}}}(\vec{\xi})(b_{i_1} - a_{i_1})(b_{i_2} - a_{i_2})\dots(b_{i_{k+1}} - a_{i_{k+1}}).$$

Proof. As A is open and convex, we may find $\epsilon > 0$ so that the parametrised line

$$\vec{r}\colon (-\epsilon, 1+\epsilon) \longrightarrow \mathbb{R}^n \qquad \text{given by} \qquad \vec{r}(t) = \vec{a} + t(\vec{b} - \vec{a}),$$

is contained in A. Let

$$g\colon (-\epsilon, 1+\epsilon) \longrightarrow \mathbb{R},$$

be the composition of $\vec{r}(t)$ and $f(\vec{x})$.

Claim 19.5.

$$P_{0,k}g(t) = P_{\vec{a},k}f(\vec{r}(t)).$$

Proof of (19.5). This is just the chain rule;

$$g'(t) = \sum_{1\leq i\leq n} \frac{\partial f}{\partial x_i}(\vec{r}(t))(b_i - a_i)$$

$$g''(t) = \sum_{1\leq i\leq j\leq n} \frac{\partial^2 f}{\partial x_i \partial x_j}(\vec{r}(t))(b_i - a_i)(b_j - a_j)$$

and so on. □

So the result follows by the one variable result. □

We can write out the first few terms of the Taylor series of f and get something interesting. Let $\vec{h} = \vec{x} - \vec{a}$. Then

$$P_{\vec{a},2}f(x) = f(\vec{a}) + \sum_{1 \le i \le n} \frac{\partial f}{\partial x_i}(\vec{a})h_i + 1/2 \sum_{1 \le i < j \le n} \frac{\partial^2 f}{\partial x_i \partial x_j}(\vec{a})h_i h_j.$$

The middle term is the same as multiplying the row vector formed by the gradient of f,

$$\nabla f(\vec{a}) = (\frac{\partial f}{\partial x_1}(\vec{a}), \frac{\partial f}{\partial x_2}(\vec{a}), \dots \frac{\partial f}{\partial x_n}(\vec{a})),$$

and the column vector given by $\vec{h}$. The last term is the same as multiplying the matrix with entries

$$\frac{\partial^2 f}{\partial x_i \partial x_j}(\vec{a}),$$

on the left by $\vec{h}$ and on the right by the column vector given by $\vec{h}$ and dividing by 2.

The matrix

$$Hf(\vec{a}) = (\frac{\partial^2 f}{\partial x_i \partial x_j}(\vec{a})),$$

is called the **Hessian** of $f(\vec{x})$.