Extreme Values of Functions of Several Variables

Calculus III Handout

March 17, 2009

Recall that if S is a subset of n-dimensional space and P is a point of S we say that P is a point in the *interior* of S or a point *inside* S if there is some (small) positive number r such that every point of n-dimensional space within distance r of P is a point of S.

Recall that a function f of n variables is *differentiable* at a point inside its domain if it admits first order approximation by a linear function near the given point.

Theorem. *If a function f of n variables has an extreme value for the subset S of its domain at a point P of S that is a point* inside *the domain of f where f is differentiable, then the gradient vector $\nabla f(P)$ of f at P must be perpendicular to the tangent vector at P of every differentiably parameterized curve lying in S and passing through P.*

Proof. Let $G(t)$ be a differentiably parameterized curve contained in S and passing through P when $t = a$. Since S is contained in the domain of f, the function $h(t) = f(G(t))$ is defined for all values of t for which $G(t)$ is defined, and since f is differentiable at $P = G(a)$, the function h is differentiable at a. In fact, the "chain rule" tells us that

$$h'(a) = \nabla f(P) \cdot G'(a) \quad .$$

Since f has an extreme value relative to the set S at the point P and each $G(t)$ is in S, it follows that h, a function of one variable, has a local extreme value at $t = a$, and, therefore, that $h'(a) = 0$. Consequently, $\nabla f(P)$ is perpendicular to the tangent vector $G'(a)$ of the curve at P.

Corollary 1. *If a function f of n variables has an extreme value for the subset S of its domain at a point P of S that is a point* inside *S where f is differentiable, then the gradient vector $\nabla f(P)$ must be the zero vector.*

Proof. If P is a point *inside* S then every sufficiently short line segment passing through P must be perpendicular to $\nabla f(P)$, which means that every vector must be perpendicular to $\nabla f(P)$.

Corollary 2. *If a function f of n variables has an extreme value for the subset $S = \{g = 0\}$ of its domain at a point P of S where f and g are differentiable functions, then the gradient $\nabla f(P)$ of f and the gradient $\nabla g(P)$ of g must be parallel vectors.*

Proof. The statement is formally true, but probably useless if $\nabla g(P) = 0$. We assume that $\nabla g(P)$ is not the zero vector. In this case ∇g is perpendicular to the tangent hyperplane (i.e., plane if $n = 3$ or line if $n = 2$) to S at P. Every unit vector in the tangent hyperplane is tangent to some small differentiably parameterized curve segment lying in S and passing through P. Hence, by the theorem, $\nabla f(P)$ is also perpendicular to each such curve segment, and, hence, to the tangent hyperplane. Since a hyperplane has only one parallel class of normal vectors, $\nabla f(P)$ and $\nabla g(P)$ must be parallel.

Remark. The theorem is useful also in the case where f is a function of 3 variables and the constraint set S is a curve in space. Then the fact that P lies in S corresponds roughly to two equations for P and the orthogonality condition of the theorem provides, in non-degenerate situations an additional equation with the result that (usually) only finitely many such P are possible. (Among these are points that are maxima, minima, and those that are neither.) This is equivalent to the principle of "Lagrange multipliers" discussed in the text.