Appendix E. Lagrange Multipliers

Lagrange multipliers, also sometimes called *undetermined multipliers*, are used to find the stationary points of a function of several variables subject to one or more constraints.

Consider the problem of finding the maximum of a function $f(x_1, x_2)$ subject to a constraint relating x_1 and x_2, which we write in the form

$$g(x_1, x_2) = 0. \tag{E.1}$$

One approach would be to solve the constraint equation (E.1) and thus express x_2 as a function of x_1 in the form $x_2 = h(x_1)$. This can then be substituted into $f(x_1, x_2)$ to give a function of x_1 alone of the form $f(x_1, h(x_1))$. The maximum with respect to x_1 could then be found by differentiation in the usual way, to give the stationary value $x_1^\star$, with the corresponding value of x_2 given by $x_2^\star = h(x_1^\star)$.

One problem with this approach is that it may be difficult to find an analytic solution of the constraint equation that allows x_2 to be expressed as an explicit function of x_1. Also, this approach treats x_1 and x_2 differently and so spoils the natural symmetry between these variables.

A more elegant, and often simpler, approach is based on the introduction of a parameter λ called a Lagrange multiplier. We shall motivate this technique from a geometrical perspective. Consider a D-dimensional variable $\mathbf{x}$ with components $x_1, \ldots, x_D$. The constraint equation $g(\mathbf{x}) = 0$ then represents a $(D-1)$-dimensional surface in $\mathbf{x}$-space as indicated in Figure E.1.

We first note that at any point on the constraint surface the gradient $\nabla g(\mathbf{x})$ of the constraint function will be orthogonal to the surface. To see this, consider a point $\mathbf{x}$ that lies on the constraint surface, and consider a nearby point $\mathbf{x} + \boldsymbol{\epsilon}$ that also lies on the surface. If we make a Taylor expansion around $\mathbf{x}$, we have

$$g(\mathbf{x} + \boldsymbol{\epsilon}) \simeq g(\mathbf{x}) + \boldsymbol{\epsilon}^{\mathrm{T}} \nabla g(\mathbf{x}). \tag{E.2}$$

Because both $\mathbf{x}$ and $\mathbf{x} + \boldsymbol{\epsilon}$ lie on the constraint surface, we have $g(\mathbf{x}) = g(\mathbf{x} + \boldsymbol{\epsilon})$ and hence $\boldsymbol{\epsilon}^{\mathrm{T}} \nabla g(\mathbf{x}) \simeq 0$. In the limit $\|\boldsymbol{\epsilon}\| \to 0$ we have $\boldsymbol{\epsilon}^{\mathrm{T}} \nabla g(\mathbf{x}) = 0$, and because $\boldsymbol{\epsilon}$ is

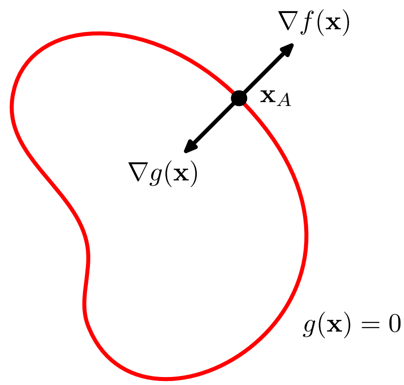

Figure E.1 A geometrical picture of the technique of Lagrange multipliers in which we seek to maximize a function $f(\mathbf{x})$, subject to the constraint $g(\mathbf{x}) = 0$. If $\mathbf{x}$ is D dimensional, the constraint $g(\mathbf{x}) = 0$ corresponds to a subspace of dimensionality $D - 1$, indicated by the red curve. The problem can be solved by optimizing the Lagrangian function $L(\mathbf{x}, \lambda) = f(\mathbf{x}) + \lambda g(\mathbf{x})$.

then parallel to the constraint surface $g(\mathbf{x}) = 0$, we see that the vector ∇g is normal to the surface.

Next we seek a point $\mathbf{x}^\star$ on the constraint surface such that $f(\mathbf{x})$ is maximized. Such a point must have the property that the vector $\nabla f(\mathbf{x})$ is also orthogonal to the constraint surface, as illustrated in Figure E.1, because otherwise we could increase the value of $f(\mathbf{x})$ by moving a short distance along the constraint surface. Thus ∇f and ∇g are parallel (or anti-parallel) vectors, and so there must exist a parameter λ such that

$$\nabla f + \lambda \nabla g = 0 \tag{E.3}$$

where $\lambda \neq 0$ is known as a *Lagrange multiplier*. Note that λ can have either sign.

At this point, it is convenient to introduce the *Lagrangian* function defined by

$$L(\mathbf{x}, \lambda) \equiv f(\mathbf{x}) + \lambda g(\mathbf{x}). \tag{E.4}$$

The constrained stationarity condition (E.3) is obtained by setting $\nabla_{\mathbf{x}} L = 0$. Furthermore, the condition $\partial L / \partial \lambda = 0$ leads to the constraint equation $g(\mathbf{x}) = 0$.

Thus to find the maximum of a function $f(\mathbf{x})$ subject to the constraint $g(\mathbf{x}) = 0$, we define the Lagrangian function given by (E.4) and we then find the stationary point of $L(\mathbf{x}, \lambda)$ with respect to both $\mathbf{x}$ and λ. For a D-dimensional vector $\mathbf{x}$, this gives $D+1$ equations that determine both the stationary point $\mathbf{x}^\star$ and the value of λ. If we are only interested in $\mathbf{x}^\star$, then we can eliminate λ from the stationarity equations without needing to find its value (hence the term 'undetermined multiplier').

As a simple example, suppose we wish to find the stationary point of the function $f(x_1, x_2) = 1 - x_1^2 - x_2^2$ subject to the constraint $g(x_1, x_2) = x_1 + x_2 - 1 = 0$, as illustrated in Figure E.2. The corresponding Lagrangian function is given by

$$L(\mathbf{x}, \lambda) = 1 - x_1^2 - x_2^2 + \lambda(x_1 + x_2 - 1). \tag{E.5}$$

The conditions for this Lagrangian to be stationary with respect to x_1, x_2, and λ give the following coupled equations:

$$-2x_1 + \lambda = 0 \tag{E.6}$$
$$-2x_2 + \lambda = 0 \tag{E.7}$$
$$x_1 + x_2 - 1 = 0. \tag{E.8}$$

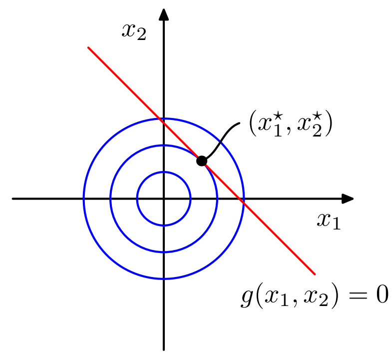

Figure E.2 A simple example of the use of Lagrange multipliers in which the aim is to maximize $f(x_1, x_2) = 1 - x_1^2 - x_2^2$ subject to the constraint $g(x_1, x_2) = 0$ where $g(x_1, x_2) = x_1 + x_2 - 1$. The circles show contours of the function $f(x_1, x_2)$, and the diagonal line shows the constraint surface $g(x_1, x_2) = 0$.

Solution of these equations then gives the stationary point as $(x_1^\star, x_2^\star) = (\frac{1}{2}, \frac{1}{2})$, and the corresponding value for the Lagrange multiplier is $\lambda = 1$.

So far, we have considered the problem of maximizing a function subject to an *equality constraint* of the form $g(\mathbf{x}) = 0$. We now consider the problem of maximizing $f(\mathbf{x})$ subject to an *inequality constraint* of the form $g(\mathbf{x}) \geqslant 0$, as illustrated in Figure E.3.

There are now two kinds of solution possible, according to whether the constrained stationary point lies in the region where $g(\mathbf{x}) > 0$, in which case the constraint is *inactive*, or whether it lies on the boundary $g(\mathbf{x}) = 0$, in which case the constraint is said to be *active*. In the former case, the function $g(\mathbf{x})$ plays no role and so the stationary condition is simply $\nabla f(\mathbf{x}) = 0$. This again corresponds to a stationary point of the Lagrange function (E.4) but this time with $\lambda = 0$. The latter case, where the solution lies on the boundary, is analogous to the equality constraint discussed previously and corresponds to a stationary point of the Lagrange function (E.4) with $\lambda \neq 0$. Now, however, the sign of the Lagrange multiplier is crucial, because the function $f(\mathbf{x})$ will only be at a maximum if its gradient is oriented away from the region $g(\mathbf{x}) > 0$, as illustrated in Figure E.3. We therefore have $\nabla f(\mathbf{x}) = -\lambda \nabla g(\mathbf{x})$ for some value of $\lambda > 0$.

For either of these two cases, the product $\lambda g(\mathbf{x}) = 0$. Thus the solution to the

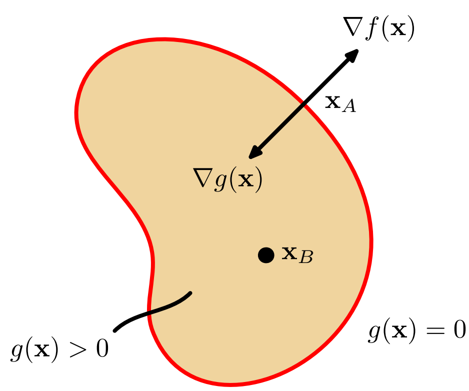

Figure E.3 Illustration of the problem of maximizing $f(\mathbf{x})$ subject to the inequality constraint $g(\mathbf{x}) \geqslant 0$.

problem of maximizing $f(\mathbf{x})$ subject to $g(\mathbf{x}) \geqslant 0$ is obtained by optimizing the Lagrange function (E.4) with respect to $\mathbf{x}$ and λ subject to the conditions

$$g(\mathbf{x}) \geqslant 0 \tag{E.9}$$

$$\lambda \geqslant 0 \tag{E.10}$$

$$\lambda g(\mathbf{x}) = 0 \tag{E.11}$$

These are known as the *Karush-Kuhn-Tucker* (KKT) conditions (Karush, 1939; Kuhn and Tucker, 1951).

Note that if we wish to minimize (rather than maximize) the function $f(\mathbf{x})$ subject to an inequality constraint $g(\mathbf{x}) \geqslant 0$, then we minimize the Lagrangian function $L(\mathbf{x}, \lambda) = f(\mathbf{x}) - \lambda g(\mathbf{x})$ with respect to $\mathbf{x}$, again subject to $\lambda \geqslant 0$.

Finally, it is straightforward to extend the technique of Lagrange multipliers to the case of multiple equality and inequality constraints. Suppose we wish to maximize $f(\mathbf{x})$ subject to $g_j(\mathbf{x}) = 0$ for $j = 1, \ldots, J$, and $h_k(\mathbf{x}) \geqslant 0$ for $k = 1, \ldots, K$. We then introduce Lagrange multipliers $\{\lambda_j\}$ and $\{\mu_k\}$, and then optimize the Lagrangian function given by

$$L(\mathbf{x}, \{\lambda_j\}, \{\mu_k\}) = f(\mathbf{x}) + \sum_{j=1}^{J} \lambda_j g_j(\mathbf{x}) + \sum_{k=1}^{K} \mu_k h_k(\mathbf{x}) \tag{E.12}$$

subject to $\mu_k \geqslant 0$ and $\mu_k h_k(\mathbf{x}) = 0$ for $k = 1, \ldots, K$. Extensions to constrained functional derivatives are similarly straightforward. For a more detailed discussion of the technique of Lagrange multipliers, see Nocedal and Wright (1999).

Appendix D