SECTION C: CONTINUOUS OPTIMISATION
LECTURE 14: THE AUGMENTED LAGRANGIAN METHOD

HONOUR SCHOOL OF MATHEMATICS, OXFORD UNIVERSITY
HILARY TERM 2005, DR RAPHAEL HAUSER

1. The Augmented Lagrangian Method. In Lecture 13 we saw that the quadratic penalty method has the disadvantage that the penalty parameter μ has to be reduced to very small values before x_k becomes feasible to high accuracy. Moreover, we pointed out that reducing μ to very small values can lead to numerical instabilities if the method is not implemented very carefully.

We will now see a related method that does not require μ_k to converge to zero, and yet in a neighbourhood of a KKT point x^* of the nonlinear optimisation problem

$$\begin{aligned} \text{(NLP)} \qquad & \min_{x\in\mathbb{R}^n} f(x) \\ & \text{s.t.} \quad g_{\mathcal{E}}(x) = 0 \\ & \qquad\; g_{\mathcal{I}}(x) \geq 0, \end{aligned}$$

the iterates x_k still converge to x^* if the LICQ and the second order sufficient optimality conditions hold at this point. In fact, μ can even be held constant after a while and the convergence of x_k continues!

1.1. Motivation. The method is motivated by the observation that if we knew the Lagrange multipliers λ^* such that (x^*, λ^*) is a KKT point for (NLP), then we could find x^* by solving the unconstrained problem

$$\min_{x\in\mathbb{R}^n} \mathcal{L}(x, \lambda^*). \tag{1.1}$$

Indeed, as already remarked in Lemma 1.2 i) of Lecture 12, the first set of KKT conditions $\nabla_x \mathcal{L}(x^*, \lambda^*) = 0$ amount to the first order necessary optimality conditions for (1.1).

Of course, λ^* is not known, but we know from Lecture 13 that one can obtain estimates $\lambda^{[k]}$ which can be used to set up the problem

$$\min_{x\in\mathbb{R}^n} \mathcal{L}(x, \lambda^{[k]}).$$

as an approximation of (1.1).

If the estimates $\lambda^{[k]}$ can be iteratively improved and made to converge to λ^*, then this can form the basis of an algorithmic framework for solving (NLP).

1.2. The Merit Function. The merit function used by this algorithm is the *augmented Lagrangian* of (NLP), defined as follows,

$$\begin{aligned} \mathcal{L}_A(x, \lambda, \mu) &= \mathcal{L}(x, \lambda) + \frac{1}{2\mu} \sum_{i\in\mathcal{I}\cup\mathcal{E}} \tilde{g}_i^2(x) \\ &= f(x) - \sum_{i\in\mathcal{I}\cup\mathcal{E}} \lambda_i g_i(x) + \sum_{i\in\mathcal{I}\cup\mathcal{E}} \frac{\tilde{g}_i(x)}{2\mu} g_i(x) \\ &= f(x) + \sum_{i\in\mathcal{I}\cup\mathcal{E}} \Big(\frac{\tilde{g}_i(x)}{2\mu} - \lambda_i\Big) g_i(x), \end{aligned}$$

where $\tilde{g}_i$ is defined as in Lecture 13,

$$\tilde{g}_i(x) = \begin{cases} g_i(x) & (i \in \mathcal{E}) \\ \min(g_i(x), 0) & (i \in \mathcal{I}). \end{cases}$$

$\mathcal{L}_A$ is thus nothing else but the Lagrangian "augmented" by the quadratic penalty term introduced in Lecture 13, ensuring that x becomes gradually more feasible as the homotopy parameter μ is reduced.

1.3. The Algorithm.

Algorithm 1.1 (AL).
S0 *Initialisation: choose the following,*
$x_0 \in \mathbb{R}^n$ *(starting point, not necessarily feasible)*
$\lambda^{[0]} \in \mathbb{R}^{|\mathcal{E}\cup\mathcal{I}|}$ *(initial "guestimate" of Lagrange multiplier vector)*
$\mu_0 > 0$ *(initial value of homotopy parameter)*
$(\tau_k)_{\mathbb{N}_0} \searrow 0$ *(error tolerance)*
S1 *For* $k = 0, 1, 2, \ldots$ *repeat*
$y^{[0]} := x_k$, $l := 0$
until $\|\nabla_x \mathcal{L}_A(y^{[l]}, \lambda^{[k]}, \mu_k)\| \leq \tau_k$ *repeat*
compute $y^{[l+1]}$ *such that* $\mathcal{L}_A(y^{[l+1]}, \lambda^{[k]}, \mu_k) < \mathcal{L}_A(y^{[l]}, \lambda^{[k]}, \mu_k)$
(using unconstrained minimisation method)
$l \leftarrow l + 1$
end
$x_{k+1} := y^{[l]}$
$\lambda_i^{[k+1]} := \lambda_i^{[k]} - \frac{\tilde{g}_i(x_{k+1})}{\mu_k}, \qquad (i \in \mathcal{E}\cup\mathcal{I}),$
$\lambda_i^{[k+1]} \leftarrow \max(0, \lambda_i^{[k+1]}), \qquad (i \in \mathcal{I})$
choose $\mu_{k+1} \in (0, \mu_k)$
end

A quick argument gives insight into why this method can be expected to converge before μ_k reaches very small values. We have

$$\nabla_x \mathcal{L}_A(x_{k+1}, \lambda^{[k]}, \mu_k) = \nabla f(x_{k+1}) - \sum_{i\in\mathcal{E}\cup\mathcal{I}} \Big(\lambda_i^{[k]} - \frac{\tilde{g}_i(x_{k+1})}{\mu_k}\Big) \nabla g_i(x_{k+1}).$$

Using $\|\nabla_x \mathcal{L}_A(x_{k+1}, \lambda^{[k]}, \mu_k)\| \leq \tau_k$, we find

$$\sum_i \Big(\lambda_i^{[k]} - \frac{\tilde{g}_i(x_{k+1})}{\mu_k}\Big) \nabla g_i(x_{k+1}) = \nabla f(x_{k+1}) + O(\tau_k).$$

Arguments similar to those given in the proof of Theorem 2.2 in Lecture 13 show that

$$\lambda_i^{[k]} - \frac{\tilde{g}_i(x_{k+1})}{\mu_k} \simeq \lambda_i^*, \qquad (i \in \mathcal{E}\cup\mathcal{I}).$$

Therefore, we have

$$\tilde{g}_i(x_{k+1}) \simeq \mu_k\big(\lambda_i^{[k]} - \lambda_i^*\big), \qquad (i \in \mathcal{E}\cup\mathcal{I}),$$

which suggests that if $\lambda^{[k]} \to \lambda^*$ then all constraint residuals converge to zero like a function $o(\mu_k)$, where

$$\lim_{\mu \to 0} \frac{o(\mu)}{\mu} = 0.$$

That is, the convergence is much faster than the $O(\mu_k)$ convergence obtained in the quadratic penalty function method.

This argument can be made precise in a neighbourhood of a point at which the sufficient second order optimality conditions hold. In fact, the following theorem indicates that μ does not have to be reduced to zero at all.

THEOREM 1.2. *Let x^* be a local minimiser of (NLP) where the LICQ and the first and second order sufficient optimality conditions are satisfied for some Lagrange multiplier vector λ^*. Then there exists a constant $\bar{\mu} > 0$ such that x^* is a strict local minimiser of*

$$\min_{x \in \mathbb{R}^n} \mathcal{L}_A(x, \lambda^*, \mu)$$

for all $\mu \in (0, \bar{\mu}]$.

For a proof see e.g. Nocedal–Wright, Theorem 17.5. Furthermore, this theorem can be strengthened to show that if $(x_k, \lambda^{[k]})$ ever enters a sufficiently small neighbourhood of (x^*, λ^*) and $\mu_k \leq \bar{\mu}$, then it is the case that $(x_k, \lambda^{[k]}) \to (x^*, \lambda^*)$ irrespective of whether μ_k is further decreased or not.

THEOREM 1.3. *For (x^*, λ^*) and $\bar{\mu}$ as in Theorem 1.2 there exist constants $M, \varepsilon, \delta > 0$ such that the following is true:*

i) if $\mu_k \leq \bar{\mu}$ and

$$\|\lambda^{[k]} - \lambda^*\| \leq \frac{\delta}{\mu_k}, \tag{1.2}$$

then the constrained minimisation problem

$$\begin{aligned} &\min_x \mathcal{L}_A(x, \lambda^{[k]}, \mu_k) \\ &s.t.\ \|x^* - x\| \leq \varepsilon \end{aligned} \tag{1.3}$$

has a unique minimiser x_{k+1} and

$$\|x^* - x_{k+1}\| \leq M\mu_k \|\lambda^{[k]} - \lambda^*\|, \tag{1.4}$$

ii) if μ_k and $\lambda^{[k]}$ are as in part i) and if $\lambda^{[k+1]}$ is chosen as in Algorithm (AL), then

$$\|\lambda^{[k+1]} - \lambda^*\| \leq M\mu_k \|\lambda^{[k]} - \lambda^*\|. \tag{1.5}$$

We conclude with a few comments on why this result is interesting.

- Without loss of generality, we may assume that $\bar{\mu} \leq (2M)^{-1}$. Note that if $(\lambda^{[k]}, \mu_k)$ satisfy the conditions of part i) of the theorem and if $x_k \in B_\varepsilon(x^*)$, then x_k is a good starting point for solving the problem (1.3) and we have

$$\begin{aligned} &x_{k+1} \in B_\varepsilon(x^*) \\ &\|\lambda^{[k+1]} - \lambda^*\| \overset{(1.2),(1.5)}{\leq} M\mu_k \frac{\delta}{\mu_k} = \delta M < \frac{\delta}{\bar{\mu}} \leq \frac{\delta}{\mu_{k+1}}, \end{aligned}$$

  where the last inequality follows from $\mu_{k+1} \leq \mu_k$. Thus, the same conditions hold again, and by induction they hold for all subsequent iterations.
- Let k_0 be the iteration where (1.4) and (1.5) first hold. Induction on k shows that

$$\|\lambda^{[k]} - \lambda^*\|, \|x_k - x^*\| \leq (M\bar{\mu})^{k-k_0} \|\lambda^{[k_0]} - \lambda^*\| \leq \frac{1}{2^{k-k_0}} \|\lambda^{[k_0]} - \lambda^*\|.$$

  This shows that $x_k \to x^*$ and $\lambda^{[k]} \to \lambda^*$ at a Q-linear rate if $\mu \leq \bar{\mu}$ is held fixed.

ADDITIONAL RECOMMENDED READING: Section 17.4, Nocedal–Wright.