Pathfollowing Algorithm for Linear Programming

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Consider the primal/dual pair of LPs:

Primal

Minimize $c^t x$
subject to $Ax = b$
$x \geq 0$

Dual

Maximize $y\,b$
subject to $yA \leq c^t$

i.e.,

Maximize $b^t y$
subject to $A^t y \leq c$

Convert dual constraints to equalities:

Primal

Minimize $c^t x$

subject to $Ax = b$

$x \geq 0$

Dual

Maximize $b^t y$

subject to $A^t y + z = c^t$

$z \geq 0$

Use barrier functions to relax the non-negativity conditions:

Primal

Minimize $c\,x - \mu \sum_{j=1}^{n} \ln(x_j)$
subject to

$$A\,x = b$$

as $x \longrightarrow 0$,
$-\mu \ln(x) \longrightarrow \infty$

Dual

Maximize $b^t y + \mu \sum_{j=1}^{n} \ln(z_j)$
subject to

$$A^t y + z = c^t$$

Use Lagrange multipliers to relax the equality constraints:

Lagrangian Functions

$$L_P(x, y) = c^t x - \mu \sum_{j=1}^{n} \ln(x_j) + y^t(Ax - b)$$

$$L_D(x,y,z) = b^t y + \mu \sum_{j=1}^{n} \ln(x_j) - x^t (A^t y + z - c)$$

The optimality conditions may be written

$$\frac{\partial L_P(x,y)}{\partial x} = 0, \quad \frac{\partial L_P(x,y)}{\partial y} = 0$$

and

$$\frac{\partial L_D(x,y,z)}{\partial x} = 0, \quad \frac{\partial L_D(x,y,z)}{\partial y} = 0, \quad \frac{\partial L_D(x,y,z)}{\partial z} = 0$$

These reduce to the following

optimality conditions

$$A\,x = b$$

$$A^t y + z = c$$

$$x_j z_j = \mu,\ j=1,2,\ \dots n$$

} *linear equations* (first two)

← *nonlinear equations* (third)

To solve the nonlinear system of equations, we might use the *Newton-Raphson* method:

Given an initial approximate solution (x^0, y^0, z^0):

an improved approximate solution is given by

$$\begin{cases} x^1 = x^0 + \delta_x \\ y^1 = y^0 + \delta_y \\ z^1 = z^0 + \delta_z \end{cases}$$

where δ_x, δ_y, and δ_z are found by solving a linear system.

Notation

$$X = \text{diag}\{x_1, x_2, \dots x_n\}$$

$$Z = \text{diag}\{z_1, z_2, \dots z_n\}$$

$$e = [\,1\,,\,1\,,\,\dots.\,1\,]$$

Then the constraints

$$x_j\, z_j = \boldsymbol{\mu},\ j=1,2,\ \dots n$$

may be written

$$X\,Z\,e = \boldsymbol{\mu}\, e$$

We wish to solve the ***nonlinear*** system

$$\begin{cases} A\,x - b = 0 \\ A^t\,y + z - c = 0 \\ \mathbf{X}\,\mathbf{Z}\,e - \boldsymbol{\mu}\,e = 0 \end{cases}$$

Newton-Raphson Method: given (x^o, y^o, z^o),
solve the ***linear*** system

$$\begin{cases} A\,\delta_x = -\left[A x^o - b\right] \\ A^t\,\delta_y + \delta_z = -\left[A^t\,y^o + z^o - c\right] \\ \mathbf{Z}\,\delta_x + \mathbf{X}\,\delta_z = -\left[\mathbf{X}\,\mathbf{Z}\,e - \boldsymbol{\mu}\,e\right] \end{cases}$$

That is, solve

Jacobian matrix →

$$\begin{bmatrix} A & 0 & 0 \\ 0 & A^t & I \\ Z & 0 & X \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix} = \begin{bmatrix} d_P \\ -d_D \\ \mu e - XZe \end{bmatrix}$$

where $d_P = b - Ax^0$ ← *primal infeasibility*

$d_D = A^t y^0 + z^0 - c$ ← *dual infeasibility*

and then compute the improved approximation

$$\begin{cases} x^1 = x^0 + \delta_x \\ y^1 = y^0 + \delta_y \\ z^1 = z^0 + \delta_z \end{cases}$$

Solving the linear system:

$$\delta_x = Z^{-1}\left[\mu e - \mathbf{X}Z\,e - \mathbf{X}\,\delta_z\right]$$

$$\delta_z = -\,d_D - A^t\,\delta_y$$

$$\Longrightarrow \left[A\,Z^{-1}\mathbf{X}\,A^t\right]\delta_y = b - \mu A\,Z^{-1}e - AZ^{-1}\mathbf{X}\,d_D$$

or

$$\delta_y = \left[A\,Z^{-1}\mathbf{X}\,A^t\right]^{-1}\left(b - \mu A\,Z^{-1}e - AZ^{-1}\mathbf{X}d_D\right)$$

Computing

$$\delta_y = \left[A\, Z^{-1} \mathbf{X}\, A^t\right]^{-1} \left(b - \mu A\, Z^{-1} e - A Z^{-1} \mathbf{X} d_D\right)$$

by using matrix inversion is computationally costly for large problems...
other methods for solving the linear system for δ_y are preferred.

After computing the step $(\delta_x, \delta_y, \delta_z)$,

$$\begin{cases} x^1 = x^0 + \delta_x \\ y^1 = y^0 + \delta_y \\ z^1 = z^0 + \delta_z \end{cases}$$

An alternative would be to go (almost) as far as possible in the x direction and the (y,z) direction:

$$\begin{cases} x^1 = x^0 + \alpha_P \, \delta_x \\ y^1 = y^0 + \alpha_D \, \delta_y \\ z^1 = z^0 + \alpha_D \, \delta_z \end{cases}$$

for stepsizes α_P and α_D, respectively.

$$\alpha_P = \tau \min_j \left\{ \frac{-x_j^0}{\delta_{xj}} : \delta_{xj} < 0 \right\}$$

$$\alpha_D = \tau \min_j \left\{ \frac{-z_j^0}{\delta_{zj}} : \delta_{zj} < 0 \right\}$$

for $0 < \tau < 1$ *e.g.,* $\tau = 0{,}995$

($\tau = 1$ will result in one of the x and z variables reaching zero!)

Generally, only one Newton-Raphson step is used, so that the nonlinear system is only approximately solved.

This completes one iteration. As $\mu \longrightarrow 0$, the values of x,y, and z will converge to the optimal primal and dual solutions.

The path followed by (x,y,z) is referred to as

the ***central path***

and the algorithm as

a ***path-following*** algorithm.

Reduction of μ:

$$\mu = \frac{c^t x^1 - b^t y^1}{\theta(n)}$$

suggested value of parameter θ:

$$\theta(n) = \begin{cases} n^2 \ \text{if} \ n \le 5{,}000 \\ n\sqrt{n} \ \text{if} \ n > 5{,}000 \end{cases}$$

Termination criterion:

$$\frac{c^t x^k - b^t y^k}{1 + \left|b^t y^k\right|} < \varepsilon$$

The number of iterations required is rather insensitive to the size n of the problem, and is usually between 20 and 80 for most problems.

Example