

Part 2: Linesearch methods for unconstrained optimization

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$$\underset{x \in \mathbb{R}^n}{\text{minimize}} \quad f(x)$$

MSc course on nonlinear optimization

ITERATIVE METHODS

- in practice very rare to be able to provide explicit minimizer
- iterative method: given starting “guess” x_0 , generate sequence $\{x_k\}$, $k = 1, 2, \dots$
- **AIM**: ensure that (a subsequence) has some favourable limiting properties:
 - satisfies first-order necessary conditions
 - satisfies second-order necessary conditions

Notation: $f_k = f(x_k)$, $g_k = g(x_k)$, $H_k = H(x_k)$.

UNCONSTRAINED MINIMIZATION

$$\underset{x \in \mathbb{R}^n}{\text{minimize}} \quad f(x)$$

where the **objective function** $f : \mathbb{R}^n \longrightarrow \mathbb{R}$

- assume that $f \in C^1$ (sometimes C^2) and Lipschitz
- often in practice this assumption violated, but not necessary

LINESEARCH METHODS

- calculate a **search direction** p_k from x_k
- ensure that this direction is a **descent direction**, i.e.,

$$g_k^T p_k < 0 \quad \text{if} \quad g_k \neq 0$$

so that, for small steps along p_k , the objective function **will** be reduced

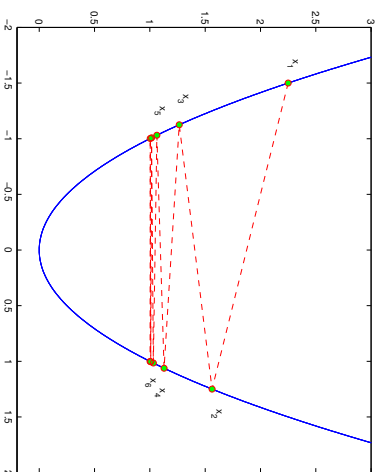
- calculate a suitable **steplength** $\alpha_k > 0$ so that

$$f(x_k + \alpha_k p_k) < f_k$$

- computation of α_k is the **linesearch**—may itself be an iteration
- generic linesearch method:

$$x_{k+1} = x_k + \alpha_k p_k$$

STEPS MIGHT BE TOO LONG



The objective function $f(x) = x^2$ and the iterates $x_{k+1} = x_k + \alpha_k p_k$ generated by the descent directions $p_k = (-1)^{k+1}$ and steps $\alpha_k = 2 + 3/2^{k+1}$ from $x_0 = 2$

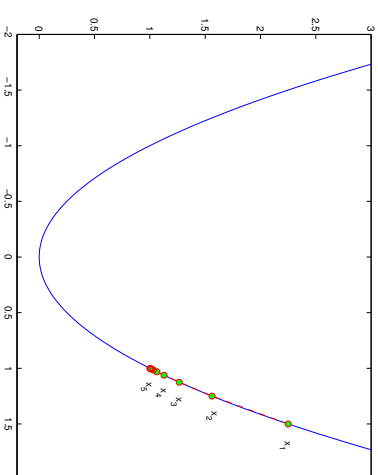
PRACTICAL LINESEARCH METHODS

- in early days, pick α_k to minimize

$$f(x_k + \alpha p_k)$$

- exact** linesearch—univariate minimization
 - rather expensive and certainly not cost effective
 - modern methods: **inexact** linesearch
 - ensure steps are neither too long nor too short
 - try to pick “useful” initial stepsize for fast convergence
 - best methods are either
 - ▷ “backtracking- Armijo” or
 - ▷ “Armijo-Goldstein”
- based

STEPS MIGHT BE TOO SHORT



The objective function $f(x) = x^2$ and the iterates $x_{k+1} = x_k + \alpha_k p_k$ generated by the descent directions $p_k = -1$ and steps $\alpha_k = 1/2^{k+1}$ from $x_0 = 2$

BACKTRACKING LINESEARCH

Procedure to find the stepsize α_k :

Given $\alpha_{\text{init}} > 0$ (e.g., $\alpha_{\text{init}} = 1$)
 let $\alpha^{(0)} = \alpha_{\text{init}}$ and $l = 0$
 Until $f(x_k + \alpha^{(l)} p_k)$ “ $<$ ” f_k
 set $\alpha^{(l+1)} = \tau \alpha^{(l)}$, where $\tau \in (0, 1)$ (e.g., $\tau = \frac{1}{2}$)
 and increase l by 1
 Set $\alpha_k = \alpha^{(l)}$

- this prevents the step from getting too small ... but does not prevent too large steps relative to decrease in f
- need to tighten requirement

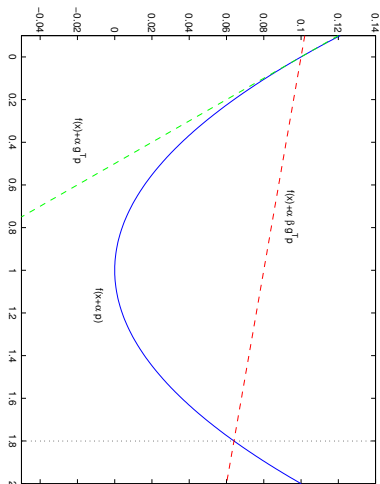
$$f(x_k + \alpha^{(l)} p_k) \text{ “} < \text{” } f_k$$

ARMJO CONDITION

In order to prevent large steps relative to decrease in f , instead require that

$$f(x_k + \alpha_k p_k) \leq f(x_k) + \alpha_k \beta g_k^T p_k$$

for some $\beta \in (0, 1)$ (e.g., $\beta = 0.1$ or even $\beta = 0.0001$)



SATISFYING THE ARMJO CONDITION

Theorem 2.1. Suppose that $f \in C^1$, that $g(x)$ is Lipschitz continuous with Lipschitz constant $\gamma(x)$, that $\beta \in (0, 1)$ and that p is a descent direction at x . Then the Armijo condition

$$f(x + \alpha p) \leq f(x) + \alpha \beta g(x)^T p$$

is satisfied for all $\alpha \in [0, \alpha_{\max}(x)]$, where

$$\alpha_{\max} = \frac{2(\beta - 1)g(x)^T p}{\gamma(x)\|p\|_2^2}$$

BACKTRACKING-ARMJO LINESEARCH

Procedure to find the stepsize α_k :

Given $\alpha_{\text{init}} > 0$ (e.g., $\alpha_{\text{init}} = 1$)
 let $\alpha^{(0)} = \alpha_{\text{init}}$ and $l = 0$
 Until $f(x_k + \alpha^{(l)} p_k) \leq f(x_k) + \alpha^{(l)} \beta g_k^T p_k$
 set $\alpha^{(l+1)} = \tau \alpha^{(l)}$, where $\tau \in (0, 1)$ (e.g., $\tau = \frac{1}{2}$)
 and increase l by 1
 Set $\alpha_k = \alpha^{(l)}$

PROOF OF THEOREM 2.1

Taylor's theorem (Theorem 1.1) +

$$\alpha \leq \frac{2(\beta - 1)g(x)^T p}{\gamma(x)\|p\|_2^2},$$

\Rightarrow

$$\begin{aligned} f(x + \alpha p) &\leq f(x) + \alpha g(x)^T p + \frac{1}{2} \gamma(x) \alpha^2 \|p\|^2 \\ &\leq f(x) + \alpha g(x)^T p + \alpha(\beta - 1)g(x)^T p \\ &= f(x) + \alpha \beta g(x)^T p \end{aligned}$$

THE ARMJO LINESEARCH TERMINATES

Corollary 2.2. Suppose that $f \in C^1$, that $g(x)$ is Lipschitz continuous with Lipschitz constant γ_k at x_k , that $\beta \in (0, 1)$ and that p_k is a descent direction at x_k . Then the stepsize generated by the backtracking-Armijo linesearch terminates with

$$\alpha_k \geq \min \left(\alpha_{\text{init}}, \frac{2\tau(\beta - 1)g_k^T p_k}{\gamma_k \|p_k\|_2^2} \right)$$

GENERIC LINESEARCH METHOD

Given an initial guess x_0 , let $k = 0$
 Until convergence:
 Find a descent direction p_k at x_k
 Compute a stepsize α_k using a
 backtracking-Armijo linesearch along p_k
 Set $x_{k+1} = x_k + \alpha_k p_k$, and increase k by 1

PROOF OF COROLLARY 2.2

Theorem 2.1 \implies linesearch will terminate as soon as $\alpha^{(l)} \leq \alpha_{\max}$. 2 cases to consider:

1. May be that α_{init} satisfies the Armijo condition $\implies \alpha_k = \alpha_{\text{init}}$.
2. Otherwise, must be a last linesearch iteration (the l -th) for which

$$\alpha^{(l)} > \alpha_{\max} \implies \alpha_k \geq \alpha^{(l+1)} = \tau \alpha^{(l)} > \tau \alpha_{\max}$$

Combining these 2 cases gives required result.

GLOBAL CONVERGENCE THEOREM

Theorem 2.3. Suppose that $f \in C^1$ and that g is Lipschitz continuous on \mathbb{R}^n . Then, for the iterates generated by the Generic Linesearch Method, either

$$g_l = 0 \text{ for some } l \geq 0$$

or

$$\lim_{k \rightarrow \infty} f_k = -\infty$$

or

$$\lim_{k \rightarrow \infty} \min (|p_k^T g_k|, |p_k^T g_k| / \|p_k\|_2) = 0.$$

PROOF OF THEOREM 2.3

Suppose that $g_k \neq 0$ for all k and that $\lim_{k \rightarrow \infty} f_k > -\infty$. Armijo \implies

$$f_{k+1} - f_k \leq \alpha_k \beta p_k^T g_k$$

for all $k \implies$ summing over first j iterations

$$f_{j+1} - f_0 \leq \sum_{k=0}^j \alpha_k \beta p_k^T g_k.$$

LHS bounded below by assumption \implies RHS bounded below. Sum composed of +ve terms \implies

$$\lim_{k \rightarrow \infty} \alpha_k |p_k^T g_k| = 0$$

Let

$$\mathcal{K}_1 \stackrel{\text{def}}{=} \left\{ k \mid \alpha_{\text{init}} > \frac{2\tau(\beta-1)g_k^T p_k}{\gamma \|p_k\|_2^2} \right\} \quad \& \quad \mathcal{K}_2 \stackrel{\text{def}}{=} \{1, 2, \dots\} \setminus \mathcal{K}_1$$

where γ is the assumed uniform Lipschitz constant.

METHOD OF STEEPEST DESCENT

The search direction

$$p_k = -g_k$$

gives the so-called **steepest-descent** direction.

◦ p_k is a descent direction

◦ p_k solves the problem

$$\underset{p \in \mathbb{R}^n}{\text{minimize}} \quad m_k^L(x_k + p) \stackrel{\text{def}}{=} f_k + g_k^T p \quad \text{subject to} \quad \|p\|_2 = \|g_k\|_2$$

Any method that uses the steepest-descent direction is a

method of steepest descent.

For $k \in \mathcal{K}_1$,

$$\alpha_k \geq \frac{2\tau(\beta-1)g_k^T p_k}{\gamma \|p_k\|_2^2}$$

\implies

$$\alpha_k p_k^T g_k \leq \frac{2\tau(\beta-1)}{\gamma} \left(\frac{g_k^T p_k}{\|p_k\|} \right)^2 < 0$$

\implies

$$\lim_{k \in \mathcal{K}_1 \rightarrow \infty} \frac{|p_k^T g_k|}{\|p_k\|_2} = 0. \tag{1}$$

For $k \in \mathcal{K}_2$,

$$\alpha_k \geq \alpha_{\text{init}}$$

\implies

$$\lim_{k \in \mathcal{K}_2 \rightarrow \infty} |p_k^T g_k| = 0. \tag{2}$$

Combining (1) and (2) gives the required result..

GLOBAL CONVERGENCE FOR STEEPEST DESCENT

Theorem 2.4. Suppose that $f \in C^1$ and that g is Lipschitz continuous on \mathbb{R}^n . Then, for the iterates generated by the Generic Linesearch Method using the steepest-descent direction, either

$$g_l = 0 \quad \text{for some } l \geq 0$$

or

$$\lim_{k \rightarrow \infty} f_k = -\infty$$

or

$$\lim_{k \rightarrow \infty} g_k = 0.$$

PROOF OF THEOREM 2.4

Follows immediately from Theorem 2.3, since

$$\min (|p_k^T g_k|, |p_k^T g_k|/\|p_k\|_2) = \|g_k\|_2 \min(1, \|g_k\|_2)$$

and thus

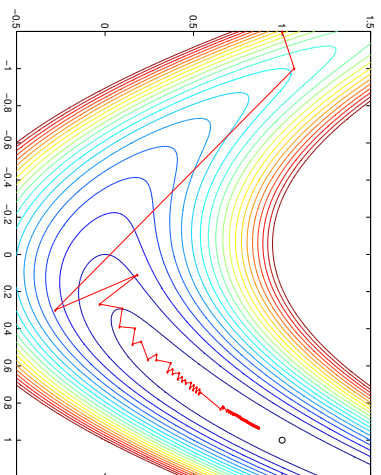
$$\lim_{k \rightarrow \infty} \min (|p_k^T g_k|, |p_k^T g_k|/\|p_k\|_2) = 0$$

implies that $\lim_{k \rightarrow \infty} g_k = 0$.

METHOD OF STEEPEST DESCENT (cont.)

- archetypical globally convergent method
- many other methods resort to steepest descent in bad cases
- not scale invariant
- convergence is usually very (very!) slow (linear)
- numerically often not convergent at all

STEEPEST DESCENT EXAMPLE



Contours for the objective function $f(x, y) = 10(y - x^2)^2 + (x - 1)^2$, and the iterates generated by the Generic Linesearch steepest-descent method

MORE GENERAL DESCENT METHODS

Let B_k be a symmetric, positive definite matrix, and define the search direction p_k so that

$$B_k p_k = -g_k$$

Then

- p_k is a descent direction
- p_k solves the problem

$$\underset{p \in \mathbb{R}^n}{\text{minimize}} \quad m_k^Q(x_k + p) \triangleq f_k + g_k^T p + \frac{1}{2} p^T B_k p$$

- if the Hessian H_k is positive definite, and $B_k = H_k$, this is **Newton's method**

MORE GENERAL GLOBAL CONVERGENCE

Theorem 2.5. Suppose that $f \in C^1$ and that g is Lipschitz continuous on \mathbb{R}^n . Then, for the iterates generated by the Generic Linesearch Method using the more general descent direction, either

$$g_l = 0 \text{ for some } l \geq 0$$

or

$$\lim_{k \rightarrow \infty} f_k = -\infty$$

or

$$\lim_{k \rightarrow \infty} g_k = 0$$

provided that the eigenvalues of B_k are uniformly bounded and bounded away from zero.

\Rightarrow

$$\frac{|p_k^T g_k|}{\|p_k\|_2} \geq \frac{\lambda_{\min}}{\lambda_{\max}} \|g_k\|_2$$

Thus

$$\min (|p_k^T g_k|, |p_k^T g_k| / \|p_k\|_2) \geq \frac{\|g_k\|_2}{\lambda_{\max}} \min (\lambda_{\min}, \|g_k\|_2)$$

\Rightarrow

$$\lim_{k \rightarrow \infty} \min (|p_k^T g_k|, |p_k^T g_k| / \|p_k\|_2) = 0$$

\Rightarrow

$$\lim_{k \rightarrow \infty} g_k = 0.$$

PROOF OF THEOREM 2.5

Let $\lambda_{\min}(B_k)$ and $\lambda_{\max}(B_k)$ be the smallest and largest eigenvalues of B_k . By assumption, there are bounds $\lambda_{\min} > 0$ and λ_{\max} such that

$$\lambda_{\min} \leq \lambda_{\min}(B_k) \leq \frac{s^T B_k s}{\|s\|^2} \leq \lambda_{\max}(B_k) \leq \lambda_{\max}$$

and thus that

$$\lambda_{\max}^{-1} \leq \lambda_{\max}^{-1}(B_k) = \lambda_{\min}(B_k^{-1}) \leq \frac{s^T B_k^{-1} s}{\|s\|^2} \leq \lambda_{\max}(B_k^{-1}) = \lambda_{\min}^{-1}(B_k) \leq \lambda_{\min}^{-1}$$

for any nonzero vector s . Thus

$$|p_k^T g_k| = |g_k^T B_k^{-1} g_k| \geq \lambda_{\min}(B_k^{-1}) \|g_k\|_2^2 \geq \lambda_{\min}^{-1} \|g_k\|_2^2$$

In addition

$$\|p_k\|_2^2 = g_k^T B_k^{-2} g_k \leq \lambda_{\max}(B_k^{-2}) \|g_k\|_2^2 \leq \lambda_{\max}^{-2} \|g_k\|_2^2,$$

\Rightarrow

$$\|p_k\|_2 \leq \lambda_{\min}^{-1} \|g_k\|_2$$

MORE GENERAL DESCENT METHODS (cont.)

- may be viewed as “scaled” steepest descent
- convergence is often faster than steepest descent
- can be made scale invariant for suitable B_k

CONVERGENCE OF NEWTON'S METHOD

Theorem 2.6. Suppose that $f \in C^2$ and that H is Lipschitz continuous on \mathbb{R}^n . Then suppose that the iterates generated by the Generic Linesearch Method with $\alpha_{\text{init}} = 1$ and $\beta < \frac{1}{2}$, in which the search direction is chosen to be the Newton direction $p_k = -H_k^{-1}g_k$ whenever possible, has a limit point x_* for which $H(x_*)$ is positive definite. Then

- (i) $\alpha_k = 1$ for all sufficiently large k ,
- (ii) the entire sequence $\{x_k\}$ converges to x_* , and
- (iii) the rate is Q -quadratic, i.e, there is a constant $\kappa \geq 0$.

$$\lim_{k \rightarrow \infty} \frac{\|x_{k+1} - x_*\|_2}{\|x_k - x_*\|_2^2} \leq \kappa.$$

PROOF OF THEOREM 2.6

Consider $\lim_{k \in \mathcal{K}} x_k = x_*$. Continuity $\implies H_k$ positive definite for all $k \in \mathcal{K}$ sufficiently large $\implies \exists k_0 \geq 0$:

$$p_k^T H_k p_k \geq \frac{1}{2} \lambda_{\min}(H_*) \|p_k\|_2^2$$

$\forall k_0 \leq k \in \mathcal{K}$, where $\lambda_{\min}(H_*)$ = smallest eigenvalue of $H(x_*) \implies$

$$|p_k^T g_k| = -p_k^T g_k = p_k^T H_k p_k \geq \frac{1}{2} \lambda_{\min}(H_*) \|p_k\|_2^2. \quad (3)$$

$\forall k_0 \leq k \in \mathcal{K}$, and

$$\lim_{k \in \mathcal{K} \rightarrow \infty} p_k = 0$$

since Theorem 2.5 \implies at least one of the LHS of (3) and

$$\frac{|p_k^T g_k|}{\|p_k\|_2} = -\frac{p_k^T g_k}{\|p_k\|_2} \geq \frac{1}{2} \lambda_{\min}(H_*) \|p_k\|_2$$

converges to zero for such k .

Taylor's theorem $\implies \exists z_k$ between x_k and $x_k + p_k$ such that

$$f(x_k + p_k) = f_k + p_k^T g_k + \frac{1}{2} p_k^T H(z_k) p_k.$$

Lipschitz continuity of H & $H_k p_k + g_k = 0 \implies$

$$\begin{aligned} f(x_k + p_k) - f_k - \frac{1}{2} p_k^T g_k &= \frac{1}{2} (p_k^T g_k + p_k^T H(z_k) p_k) \\ &= \frac{1}{2} (p_k^T g_k + p_k^T H_k p_k) + \frac{1}{2} (p_k^T (H(z_k) - H_k) p_k) \\ &\leq \frac{1}{2} \gamma \|z_k - x_k\|_2 \|p_k\|_2^2 \leq \frac{1}{2} \gamma \|p_k\|_2^3 \end{aligned} \quad (4)$$

Now pick k sufficiently large so that

$$\gamma \|p_k\|_2 \leq \lambda_{\min}(H_*) (1 - 2\beta).$$

+ (3) + (4) \implies

$$\begin{aligned} f(x_k + p_k) - f_k &\leq \frac{1}{2} p_k^T g_k + \frac{1}{2} \lambda_{\min}(H_*) (1 - 2\beta) \|p_k\|_2^2 \\ &\leq \frac{1}{2} (1 - (1 - 2\beta)) p_k^T g_k = \beta p_k^T g_k \end{aligned}$$

\implies unit stepsize satisfies the Armijo condition, which proves (i).

To obtain the remaining results, note that $\|H_k^{-1}\|_2 \leq 2/\lambda_{\min}(H_*)$ for all sufficiently large $k \in \mathcal{K}$. The iteration gives

$$\begin{aligned} x_{k+1} - x_* &= x_k - x_* - H_k^{-1} g_k = x_k - x_* - H_k^{-1} (g_k - g(x_*)) \\ &= H_k^{-1} (g(x_*) - g_k - H_k(x_* - x_k)). \end{aligned}$$

But Theorem 1.3 \implies

$$\|g(x_*) - g_k - H_k(x_* - x_k)\|_2 \leq \gamma \|x_* - x_k\|_2^2$$

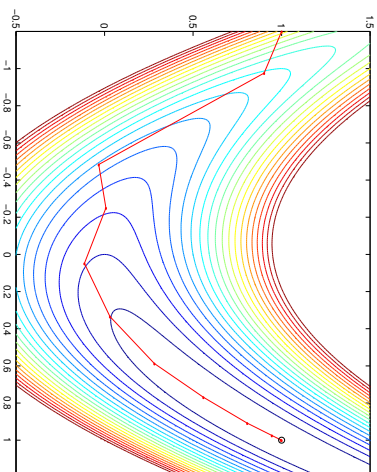
\implies

$$\|x_{k+1} - x_*\|_2 \leq \gamma \|H_k^{-1}\|_2 \|x_* - x_k\|_2^2$$

which is (iii) when $\kappa = 2\gamma/\lambda_{\min}(H_*)$.

Result (ii) follows since once iterate becomes sufficiently close to x_* , (iii) implies that next is even closer.

NEWTON METHOD EXAMPLE



Contours for the objective function $f(x, y) = 10(y - x^2)^2 + (x - 1)^2$, and the iterates generated by the Generic Linesearch Newton method

QUASI-NEWTON METHODS

Various attempts to approximate H_k :

- Finite-difference approximations:

$$(H_k)e_i \approx h^{-1}(g(x_k + he_i) - g_k)$$

for some “small” scalar $h > 0$

- Secant approximations: try to ensure the **secant condition**

$$H_{k+1}s_k = y_k, \quad \text{where } s_k = x_{k+1} - x_k \quad \text{and} \quad y_k = g_{k+1} - g_k$$

- **Symmetric Rank-1 method** (but may be indefinite or even fail):

$$H_{k+1} = H_k + \frac{(y_k - H_k s_k)(y_k - H_k s_k)^T}{(y_k - H_k s_k)^T s_k}$$

- **BFGS method**: (symmetric and positive definite if $y_k^T s_k > 0$):

$$H_{k+1} = H_k + \frac{y_k y_k^T}{y_k^T y_k} - \frac{H_k s_k s_k^T H_k}{s_k^T H_k s_k}$$

MODIFIED NEWTON METHODS

If H_k is indefinite, it is usual to solve instead

$$(H_k + M_k)p_k = -g_k$$

where

- M_k chosen so that $H_k + M_k$ is “sufficiently” positive definite
- $M_k = 0$ when H_k is itself “sufficiently” positive definite

Possibilities:

- If H_k has the spectral decomposition $H_k = Q_k D_k Q_k^T$ then

$$H_k + M_k = Q_k \max(\epsilon, |D_k|) Q_k^T$$

- $M_k = \max(0, \epsilon - \lambda_{\min}(H_k))I$
- **Modified Cholesky**: $H_k + M_k = L_k L_k^T$

MINIMIZING A CONVEX QUADRATIC MODEL

For convex models (B_k positive definite)

$$p_k = (\text{approximate}) \arg \min_{p \in \mathbb{R}^n} f_k + p^T g_k + \frac{1}{2} p^T B_k p$$

Generic convex quadratic problem: (B positive definite)

$$(\text{approximately}) \min_{p \in \mathbb{R}^n} q(p) = p^T g + \frac{1}{2} p^T B p$$

MINIMIZATION OVER A SUBSPACE

- $D^i = (d^0 : \dots : d^{i-1})$
- Subspace $\mathcal{D}^i = \{p \mid p = D^i p_d \text{ for some } p_d \in \mathbb{R}^i\}$
- $p^i = \arg \min_{p \in \mathcal{D}^i} q(p)$
- $\implies D^{iT} g^i = 0$, where $g^i = Bp^i + g$
- $p^{i-1} \in \mathcal{D}^i$
- $\implies p^i = p^{i-1} + D^i p_d^i$, where
- $p_d^i = \arg \min_{p_d \in \mathbb{R}^i} D^{iT} D^i g^{i-1} + \frac{1}{2} p_d^T D^{iT} B D^i p_d$
- $= -(D^{iT} B D^i)^{-1} D^{iT} g^{i-1} = -d^{i-1T} g^{i-1} (D^{iT} B D^i)^{-1} e_i$
- $\implies p^i = p^{i-1} - d^{i-1T} g^{i-1} (D^{iT} B D^i)^{-1} e_i$

CONJUGATE-GRADIENT METHOD

Given $p^0 = 0$, set $g^0 = g$, $d^0 = -g$ and $i = 0$.
 Until g^i "small" iterate

$$\alpha^i = -g^{iT} d^i / d^{iT} B d^i$$

$$p^{i+1} = p^i + \alpha^i d^i$$

$$g^{i+1} = g^i + \alpha^i B d^i$$

$$\beta^i = \|g^{i+1}\|_2^2 / \|g^i\|_2^2$$

$$d^{i+1} = -g^{i+1} + \beta^i d^i$$

and increase i by 1

Important features

- $d^{iT} g^{i+1} = 0$ for all $j = 0, \dots, i \implies \alpha^i = \|g^i\|_2^2 / d^{iT} B d^i$
- $g^{iT} g^{i+1} = 0$ for all $j = 0, \dots, i$
- $g^T p^i < 0$ for $i = 1, \dots, n \implies$ descent direction for any $p_k = p^i$

MINIMIZATION OVER A CONJUGATE SUBSPACE

Minimizer over \mathcal{D}^i : $p^i = p^{i-1} - d^{i-1T} g^{i-1} (D^{iT} B D^i)^{-1} e_i$

Suppose in addition the members of \mathcal{D}^i are B -conjugate:

- **B-conjugacy**: $d_i^T B d_j = 0$ ($i \neq j$)
- $\implies p^i = p^{i-1} + \alpha^{i-1} d^{i-1}$, where
- $\alpha^{i-1} = -\frac{d^{i-1T} g^{i-1}}{d^{i-1T} B d^{i-1}}$

Building a B-conjugate subspace

Since g^i is independent of \mathcal{D}^i , let $d^i = -g^i + \sum_{j=0}^{i-1} \beta^{ij} d^j$

- choose β^{ij} so that d^i is B -conjugate to \mathcal{D}^i

$$\implies \beta^{ij} = 0 \ (j < i-1), \beta^{i,i-1} \equiv \beta^i = \frac{\|g^i\|_2^2}{\|g^{i-1}\|_2^2}$$

CONJUGATE GRADIENT METHOD GIVES DESCENT

$$g^{i-1T} d^{i-1} = d^{i-1T} (g + B p^{i-1}) = d^{i-1T} g + \sum_{j=0}^{i-2} \alpha_j d^{i-1T} B d^j = d^{i-1T} g$$

p^i minimizes $q(p)$ in $\mathcal{D}^i \implies$

$$p^i = p^{i-1} - \frac{g^{i-1T} d^{i-1}}{d^{i-1T} B d^{i-1}} d^{i-1} = p^{i-1} - \frac{g^T d^{i-1}}{d^{i-1T} B d^{i-1}} d^{i-1}.$$

\implies

$$g^T p^i = g^T p^{i-1} - \frac{(g^T d^{i-1})^2}{d^{i-1T} B d^{i-1}},$$

$\implies g^T p^i < g^T p^{i-1} \implies$ (induction)

$$g^T p^i < 0$$

since

$$g^T p^1 = -\frac{\|g\|_2^4}{g^T B g} < 0.$$

$\implies p_k = p^i$ is a descent direction