

## Multivariate Optimization 2

### Solution 1: Gradient Descent

```
(a) library(ggplot2)

c1 = c(-1.1, 1.1)
c2 = c(0.8, -0.8)

S2 = matrix(c(1.1, -0.9, -0.9, 1.1), nrow = 2)
S2_inv = solve(S2)

rho <- function(u) {ifelse(abs(u) < 1, (1 - u^2)^2, 0)}

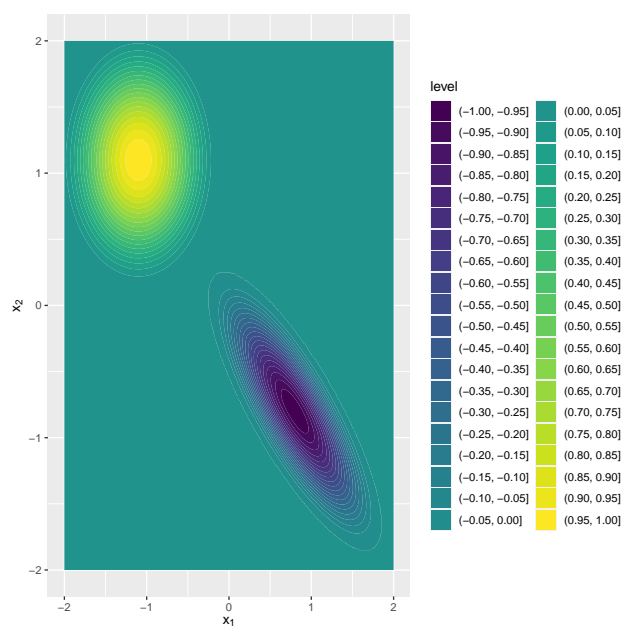
dist1 <- function(x) {sqrt((x - c1) %*% (x - c1))}
dist2 <- function(x) {sqrt((x - c2) %*% S2_inv %*% (x - c2))}

f <- function(x) {rho(dist1(x)) - rho(dist2(x))}

x = seq(-2, 2, by=0.01)
xx = expand.grid(X1 = x, X2 = x)

fxx = apply(xx, 1, f)
df = data.frame(xx = xx, fxx = fxx)

cont_plot = ggplot() +
  geom_contour_filled(data = df, aes(x = xx.X1, y = xx.X2, z = fxx),
    binwidth = 0.05) +
  xlab(expression(x[1])) +
  ylab(expression(x[2]))
cont_plot
```



- (b) First we analyze  $\rho(u)$  for  $|u| < 1$  :  $(1 - u^2)^2 = 0 \iff (1 - u^2) = 0 \iff u^2 = 1 \Rightarrow \rho(u) \neq 0$  for  $u^2 < 1$  and  $\rho(u) = 0$  for  $u^2 \geq 1$ .

We can check this condition for both squared distances around the centers  $\mathbf{c}_1, \mathbf{c}_2$ :

(i)  $\|\mathbf{x} - \mathbf{c}_1\|_{S_1}^2 < 1 \iff \|\mathbf{x} - \mathbf{c}_1\|_2^2 < 1$  (unit circle around  $\mathbf{c}_1$ )

(ii)  $\|\mathbf{x} - \mathbf{c}_2\|_{S_2}^2 = (\mathbf{x} - \mathbf{c}_2)^\top \begin{pmatrix} 1.1 & -0.9 \\ -0.9 & 1.1 \end{pmatrix}^{-1} (\mathbf{x} - \mathbf{c}_2) < 1$  (ellipse around  $\mathbf{c}_2$ )

In order to find the smallest enclosing circle of the ellipse we can use the eigendecomposition of  $S_2$  :

$$\det(S_2 - \lambda \mathbf{I}) = 0 \iff \det \begin{pmatrix} 1.1 - \lambda & -0.9 \\ -0.9 & 1.1 - \lambda \end{pmatrix} = 0 \iff \lambda^2 - 2.2\lambda + 0.4 = 0 \iff \lambda_1 = 2.0, \lambda_2 = 0.2$$

$\Rightarrow$  Eigenvalues  $\mu_1, \mu_2$  of  $S_2^{-1}$  are  $\mu_i = 1/\lambda_i$ .

With this we get

$$\|\mathbf{x} - \mathbf{c}_2\|_{S_2}^2 < 1 \iff (\mathbf{x} - \mathbf{c}_2)^\top \mathbf{V}^\top \begin{pmatrix} 5 & 0 \\ 0 & 0.5 \end{pmatrix} \mathbf{V} (\mathbf{x} - \mathbf{c}_2) < 1 \text{ with } |\det \mathbf{V}| = 1.$$

$\Rightarrow$  the circle around  $\mathbf{c}_2$  with radius  $\sqrt{1/0.5} = \sqrt{2}$  encloses the ellipse.

$\|\mathbf{c}_2 - \mathbf{c}_1\|_2 = \sqrt{2 \cdot 1.9^2} \approx 2.69 > 1 + \sqrt{2} \approx 2.41 \Rightarrow$  the circles can not intersect

$\Rightarrow$  the unit circle around  $\mathbf{c}_1$  and the ellipse around  $\mathbf{c}_2$  can not intersect  $\Rightarrow$  only  $\rho(\|\mathbf{x} - \mathbf{c}_1\|_{S_1})$  or  $\rho(\|\mathbf{x} - \mathbf{c}_2\|_{S_2})$  can be non-zero for a given  $\mathbf{x} \in \mathbb{R}^2$ .

- (c) Because of b) we know that we can treat  $\rho(\|\mathbf{x} - \mathbf{c}_1\|_{S_1})$  and  $\rho(\|\mathbf{x} - \mathbf{c}_2\|_{S_2})$  independently. Also it follows from  $\rho(u) \geq 0 \forall u \in \mathbb{R}, w_1 > 0$  and  $w_2 < 0$  that the global minimum must be in  $\{\mathbf{x} \in \mathbb{R}^2 \mid \|\mathbf{x} - \mathbf{c}_2\|_{S_2}^2 < 1\}$

$\frac{\partial}{\partial \mathbf{x}} \rho(\|\mathbf{x} - \mathbf{c}_2\|_{S_2}) = 2(1 - \|\mathbf{x} - \mathbf{c}_2\|_{S_2}^2) \cdot (-2) \cdot (\mathbf{x} - \mathbf{c}_2)^\top S_2^{-1} \stackrel{!}{=} \mathbf{0} \Rightarrow$  either  $\|\mathbf{x} - \mathbf{c}_2\|_{S_2}^2 = 1$  (which is the boundary) or  $\mathbf{x} = \mathbf{c}_2$ .

Since  $-\rho(1) = 0$  and  $-\rho(\|\mathbf{c}_2 - \mathbf{c}_2\|) = -1 < 0$  it follows that the global minimum must be  $\mathbf{x} = \mathbf{c}_2$ .

```
(d) # we can treat the bump functions independently b)
grad <- function(x) {
  if((x - c1) %*% (x - c1) < 1){
    return(c(-4 * c(1 - (x - c1) %*% (x - c1)) * (x - c1)))
  } else if((x - c2) %*% S2_inv %*% (x - c2) < 1){
    return(c(4 * c(1 - (x - c2) %*% S2_inv %*% (x - c2)) * (x - c2) %*% S2_inv))
  } else{
    return(c(0, 0))
  }
}

alpha = 0.15

x0 = c(-0.45, 0.5)
x1 = x0 - alpha * grad(x0)
x2 = x1 - alpha * grad(x1)

print(x1)

## [1] -0.365175  0.421700

print(x2)

## [1] -0.365175  0.421700

print(grad(x1))

## [1] 0 0
```

We can not make any further progress with GD since the gradient is exactly zero.

(e) Start with  $\mathbf{x}^{[0]} = (-0.45, 5)^\top$ .

Since  $\|\mathbf{c}_1 - \mathbf{x}^{[0]}\|_2^2 = 0.5525 < 1$  we know that  $\nabla f(\mathbf{x}^{[0]}) = -4(1 - \|\mathbf{x} - \mathbf{c}_1\|_2^2) \cdot (\mathbf{x} - \mathbf{c}_1)^\top = (-0.5655, 0.5220)$ .  
 $\mathbf{x}^{[1]} = \mathbf{x}^{[0]} - 0.15 \cdot (-0.5655, 0.5220)^\top = (-0.3652, 0.422)^\top$ .

Since  $\|\mathbf{c}_1 - \mathbf{x}^{[1]}\|_2^2 = 1.0001 > 1$  and  $\|\mathbf{c}_2 - \mathbf{x}^{[1]}\|_{S_2}^2 = 1.4323 > 1$  the gradient of  $f$  is zero at  $\mathbf{x}^{[1]}$ .  
 $\Rightarrow \mathbf{x}^{[2]} = \mathbf{x}^{[1]}$

(f) `alpha = 0.15`

```
v = c(0.4, -0.4)
phi = 0.5
x = c(-0.45, 0.5)
```

```
xs = x
for (i in 1:15){
  v = phi * v - alpha*grad(x)
  x = x + v
  xs = rbind(xs, x)
}
```

```
cont_plot +
  geom_line(data = as.data.frame(xs), aes(x=V1, y=V2), color="red")
```

