Derivative Free Optimization

Optimization and AMS Masters - University Paris Saclay

Exercices - Class 1

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I Pure Random Search (PRS)

We consider the following optimization algorithm.

[Objective: minimize $f : [-1,1]^n \to \mathbb{R}$
X_t is the estimate of the optimum at iteration t
`Input` $(U_t)_{t\geq 0}$ independent identically distributed each $U_t \sim \mathcal{U}_{[-1,1]^n}$ (unif. distributed in $[-1,1]^n$)]
`Initialize` $t = 0$, $X_0 = U_0$
`while not terminate`
    $t = t + 1$
    If $f(U_t) \leq f(X_{t-1})$
        $X_t = U_t$
    Else
        $X_t = X_{t-1}$

1. Show that for all $t \geq 0$
$$f(X_t) = \min\{f(U_0), \ldots, f(U_t)\}$$

2. We consider the simple case where $f(x) = \|x\|_\infty$ (we remind that $\|x\|_\infty := \max(|x_1|, \ldots, |x_n|)$). Show the convergence in probability of the PRS algorithm towards the optimum of f, that is prove that for all $\epsilon > 0$
$$\lim_{t\to\infty} \Pr\left(\|X_t\|_\infty \geq \epsilon\right) = 0$$
Hint: Use the equality
$$\{\|X_t\|_\infty \geq \epsilon\} = \cap_{k=0}^{t}\{\|U_k\|_\infty \geq \epsilon\}$$

3. Let $T_\epsilon = \inf\{t | X_t \in [-\epsilon, \epsilon]^n\}$ (with $\epsilon > 0$) be the first hitting time of $[-\epsilon, \epsilon]^n$.
Show that T_ϵ follows a geometric distribution with a parameter p that we will determine.
Deduce the expected value of T_ϵ, that is the expected hitting time of the PRS algorithm.

4. When we implement a DFO optimization algorithm, the cost of the algorithm is the number of calls to the objective function. Write a pseudo-code of the PRS algorithm where at each iteration the objective function f is called only once.

II Order statistics - Effect of selection

We want to illustrate the effect of selection on the distribution of candidate solutions in a stochastic algorithm. More precisely we consider a $(1, \lambda)$-ES algorithm whose state is given by $X_t \in \mathbb{R}^n$. At each iteration t, λ candidate solutions are sampled according to

$$X_i^{t+1} = X_t + U_{t+1}^i$$

with $(U_{t+1}^i)_{1 \leq i \leq \lambda}$ i.i.d. and $U_{t+1}^i \sim \mathcal{N}(0, I_d)$. Those candidate are evaluated on the function $f : \mathbb{R}^n \to \mathbb{R}$ to be minimized and then ranked according the their f values:

$$f(X_{1:\lambda}^{t+1}) \leq \ldots \leq f(X_{\lambda:\lambda}^{t+1})$$

where $i{:}\lambda$ denotes the index of the i^{th} best candidate solution. The best candidate solution is then selected that is

$$X_{t+1} = X_{1:\lambda}^{t+1} \ .$$

We will compute for the linear function $f(x) = x_1$ to be minimized the conditional distribution of $X_{1:\lambda}^{t+1}$ (i.e. after selection) and compare it to the distribution of X_i^{t+1} (i.e. before selection).

1. What is the distribution of X_i^{t+1} conditional to X_t? Deduce the density of each coordinate of X_i^{t+1}.

We remind that given λ random variables independent and identically distributed $Y_1, Y_2, \ldots, Y_\lambda$, the order statistics $Y_{(1)}, Y_{(2)}, \ldots, Y_{(\lambda)}$ are random variables defined by sorting the realizations of $Y_1, Y_2, \ldots, Y_\lambda$ in increasing order. We consider that each random variable Y_i admits a density $f(x)$ and we denote $F(x)$ the cumulative distribution function, that is $F(x) = \Pr(Y \leq x)$.

2. Compute the cumulative distribution of $Y_{(1)}$ and deduce the density of $Y_{(1)}$.
3. Let $U_{1:\lambda}^{t+1}$ be the random vector such that

   $$X_{1:\lambda}^{t+1} = X_t + U_{1:\lambda}^{t+1}$$

   Express for the minimization of the linear function $f(x) = x_1$, the first coordinate of $U_{1:\lambda}^{t+1}$ as an order statistic.
4. Deduce the conditional distribution and conditional density of the random vector $X_{1:\lambda}^{t+1}$.

II Adaptive step-size algorithms

We are going to test the convergence of several algorithms on some test functions, in particular on the so-called sphere function

$$f_{\text{sphere}}(\mathbf{x}) = \sum_{i=1}^{n} \mathbf{x}_i^2$$

and the ellipsoid function

$$f_{\text{elli}}(\mathbf{x}) = \sum_{i=1}^{n} (100^{\frac{i-1}{n-1}} \mathbf{x}_i)^2 \ .$$

1. What is the condition number associated to the Hessian matrix of the functions above? Are the functions ill-conditioned?

2. Use Matlab to implement the functions. We can create two functions `fsphere.m` and `felli.m` that take as input a vector $\mathbf{x}$ and returns $f(\mathbf{x})$.

The $(1+1)$-ES algorithm is on of the simplest stochastic search method for numerical optimization. We will start by implementing a $(1+1)$-ES with constant step-size. The pseudo-code of the algorithm is given by

```
Initialize x ∈ ℝ^n and σ > 0
while not terminate
      x' = x + σN(0, I)
      if f(x') ≤ f(x)
            x = x'
```

where $\mathcal{N}(\mathbf{0}, \boldsymbol{I})$ denotes a Gaussian vector with mean $\mathbf{0}$ and covariance matrix equal to the identity.

1. Implement the algorithm in Matlab. You can write a function that takes as input an initial vector $\mathbf{x}$, an initial step-size σ and a maximum number of function evaluations and returns a vector where you have recorded at each iteration the best objective function value.

2. Use the algorithm to minimize the sphere function in dimension $n = 5$. We will take as initial search point $\mathbf{x}^0 = (1, \ldots, 1)$ [`x=ones(1,5)`] and initial step-size $\sigma = 10^{-3}$ [`sigma=1e-3`] and stopping criterion a maximum number of function evaluations equal to 2×10^4.

3. Plot the evolution of the function value of the best solution versus the number of iterations (or function evaluations). We will use a log scale for the y-axis (`semilogy`).

4. Explain the three phases observed on the figure.

   To accelerate the convergence, we will implement a step-size adaptive algorithm, i.e. σ is not fixed once for all. The method to adapt the step-size is called one-fifth success rule. The pseudo-code of the $(1+1)$-ES with one-fifth success rule is given by:

```
Initialize x ∈ ℝ^n and σ > 0
while not terminate
      x' = x + σN(0, I)
      if f(x') ≤ f(x)
            x = x'
            σ = 1.5 σ
      else
            σ = (1.5)^(-1/4) σ
```

5. Implement the (1+1)-ES with one-fifth success rule and test the algorithm on the sphere function $f_{\mathrm{sphere}}(x)$ in dimension 5 ($n = 5$) using $\mathbf{x}^0 = (1, \ldots, 1)$, $\sigma_0 = 10^{-3}$ and as stopping criterion a maximum number of function evaluations equal to 6×10^2. Plot the evolution of the square root of the best function value at each iteration versus the number of iterations. Use a logarithmic scale for the y-axis. Compare to the plot obtained on Question 3. Plot also on the same graph the evolution of the step-size.

6. Use the algorithm to minimize the function f_{elli} in dimension $n = 5$. Plot the evolution of the objective function value of the best solution versus the number of iterations. Why is the $(1+1)$-ES with one-fifth success much slower on f_{elli} than on f_{sphere} ?

7. Same question with the function

$$f_{\mathrm{Rosenbrock}}(x) = \sum_{i=1}^{n-1} (100(x_i^2 - x_{i+1})^2 + (x_i - 1)^2) \ .$$

8. We now consider the functions, $g(f_{\mathrm{sphere}})$ and $g(f_{\mathrm{elli}})$ where $g : \mathbb{R} \to \mathbb{R}, y \mapsto y^{1/4}$. Modify your implementation in Questions 5 and 6 so as to save at each iteration the distance between $\mathbf{x}$ and the optimum. Plot the evolution of the distance to the optimum versus the number of function evaluations on the functions f_{sphere} and $g(f_{\mathrm{sphere}})$ as well as on the functions f_{elli} and $g(f_{\mathrm{elli}})$. What do you observe? Explain.