

# Blackbox optimization: Algorithms and applications

Sébastien Le Digabel



**POLYTECHNIQUE  
MONTREAL**  
TECHNOLOGICAL  
UNIVERSITY

CIROQUO, 2023-06-29

# Presentation outline

Introduction

Example 1: Aircraft takeoff trajectories

The MADS algorithm

Example 2: Solar thermal power plant

The NOMAD software package

References

## Introduction

Example 1: Aircraft takeoff trajectories

The MADS algorithm

Example 2: Solar thermal power plant

The NOMAD software package

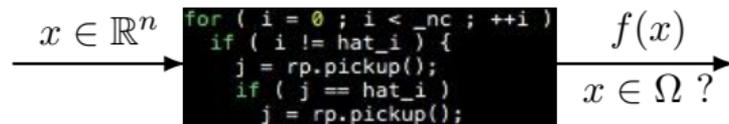
References

# Blackbox / Derivative-Free Optimization

We consider

$$\min_{x \in \Omega} f(x)$$

where the evaluations of  $f$  and the functions defining  $\Omega$  are the result of a computer simulation (a **blackbox**)



- ▶ Each call to the simulation may be expensive
- ▶ The simulation can fail
- ▶ Sometimes  $f(x) \neq f(x)$
- ▶ Derivatives are not available and cannot be approximated

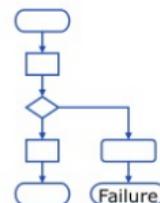
## Blackboxes as illustrated by a Boeing engineer



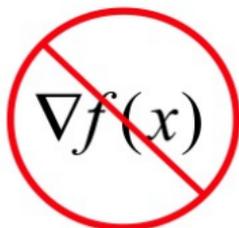
Long runtime



Large memory  
requirement



Software  
might fail



No derivatives  
available



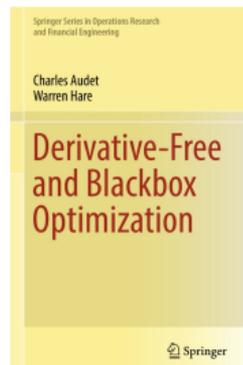
Local  
optima



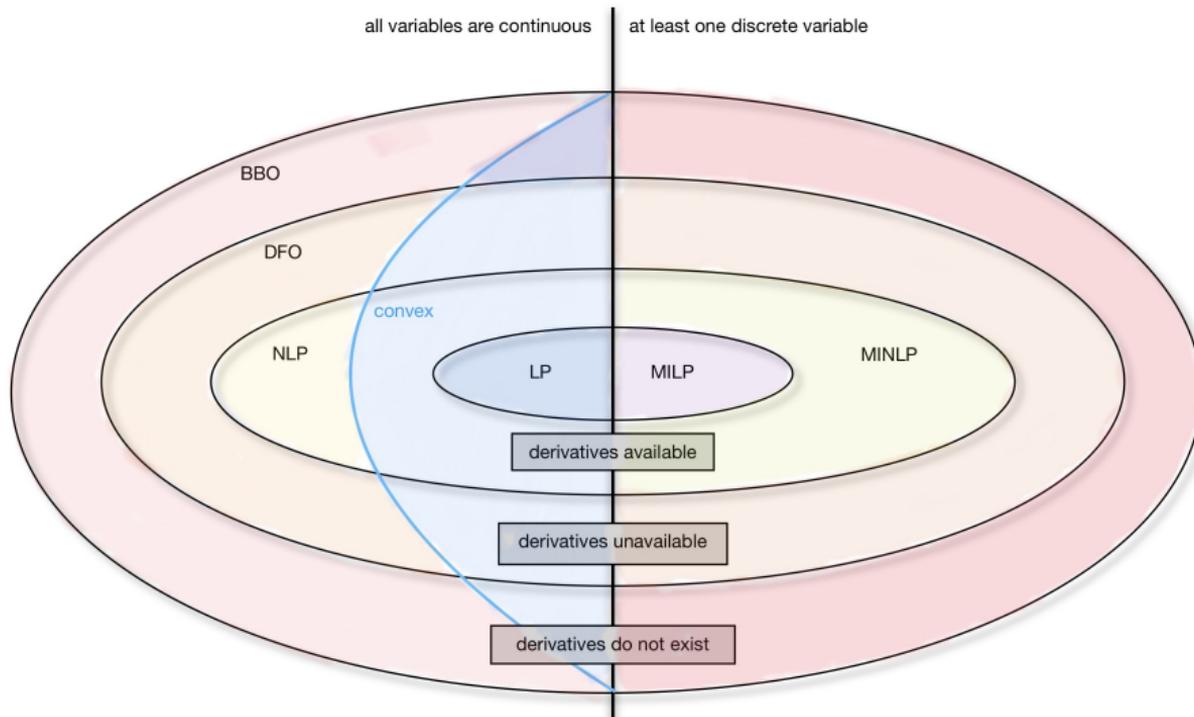
Non-smooth,  
noisy

## Terms

- ▶ “*Derivative-Free Optimization (DFO)* is the mathematical study of optimization algorithms that do not use derivatives” [Audet and Hare, 2017]
  - ▶ Optimization without using derivatives
  - ▶ Derivatives may exist but are not available
  - ▶ Obj./constraints may be analytical or given by a blackbox
  
- ▶ “*Blackbox Optimization (BBO)* is the study of design and analysis of algorithms that assume the objective and/or constraints functions are given by blackboxes” [Audet and Hare, 2017]
  - ▶ A simulation, or a blackbox, is involved
  - ▶ Obj./constraints may be analytical functions of the outputs
  - ▶ Derivatives may be available (ex.: PDEs)
  - ▶ Sometimes referred as *Simulation-Based Optimization (SBO)*



# Optimization: Global view



## Introduction

### **Example 1: Aircraft takeoff trajectories**

The MADS algorithm

Example 2: Solar thermal power plant

The NOMAD software package

References

## Aircraft takeoff trajectories

- ▶ [Torres et al., 2011]

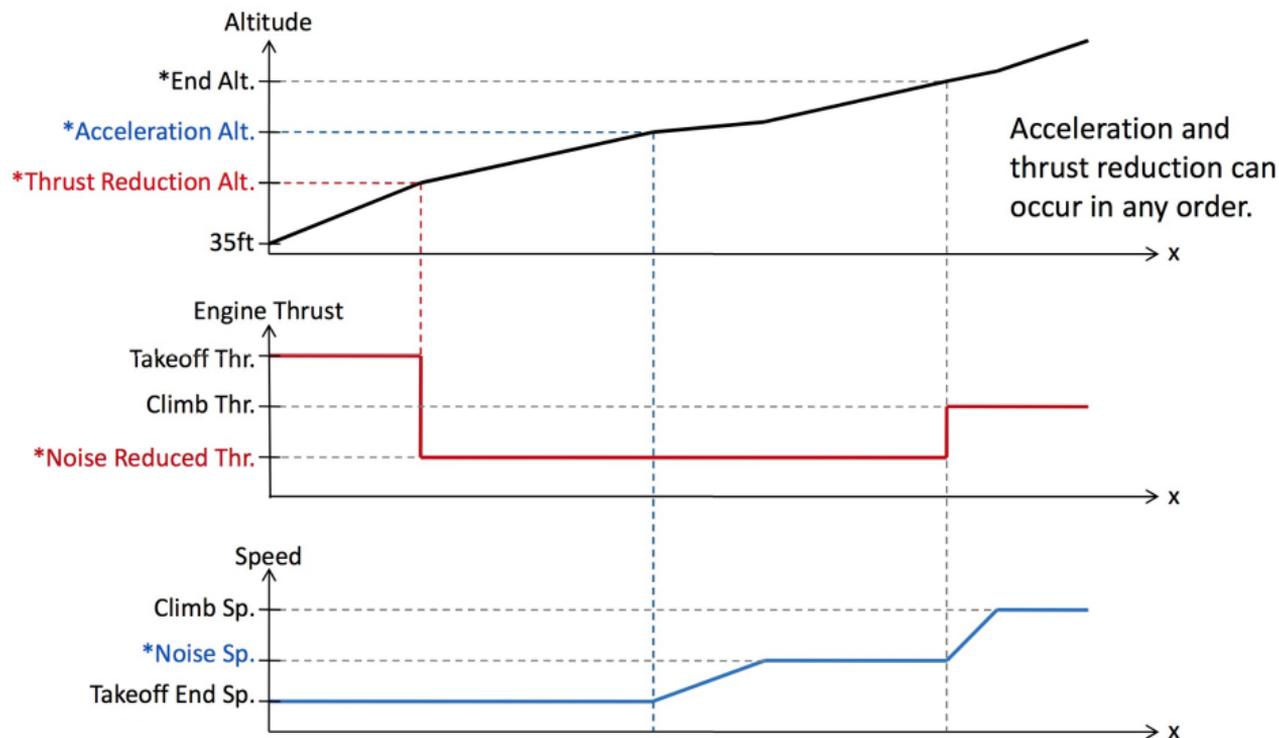


- ▶ **AIRBUS** problem involving (among others): O. Babando, C. Bes, J. Chaptal, J.-B. Hiriart-Urruty, B. Talgorn, B. Tessier, and R. Torres
- ▶ **Biobjective optimization** problem

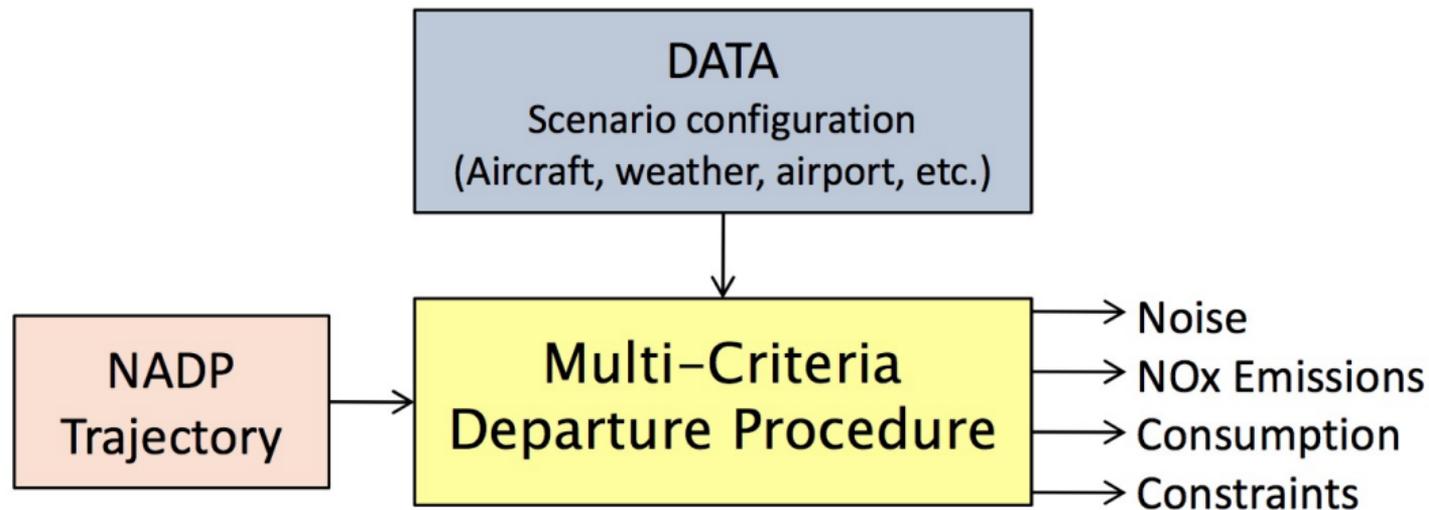
## Definition of the optimization problem

- ▶ Concept : Optimization of vertical flight path based on procedures designed to reduce noise emission at departure to protect airport vicinity
- ▶ Minimization of environmental and economical impact: **Noise** and **fuel consumption**
- ▶ **Variables** define the NADP (Noise Abatement Departure Procedure): During departure phase, the aircraft will target its climb configuration:
  - ▶ Increase the speed up to climb speed (acceleration phase)
  - ▶ Reduce the engine rate to climb thrust (reduction phase)
  - ▶ Gain altitude

## Parametric Trajectory: 5 optimization variables (\*)



## The blackbox: Multi-Criteria Departure Procedure



One evaluation  $\simeq$  2 seconds

## Special features

- ▶ Must execute on different platforms including some old Solaris distributions
- ▶ The best trajectory parameters are returned to the pilot who enters them in the aircraft system manually → **the less decimals the better**
- ▶ Finite precision on optimization parameters: Discretization of optimization variables → **granular variables** [Audet et al., 2019]

## Introduction

## Example 1: Aircraft takeoff trajectories

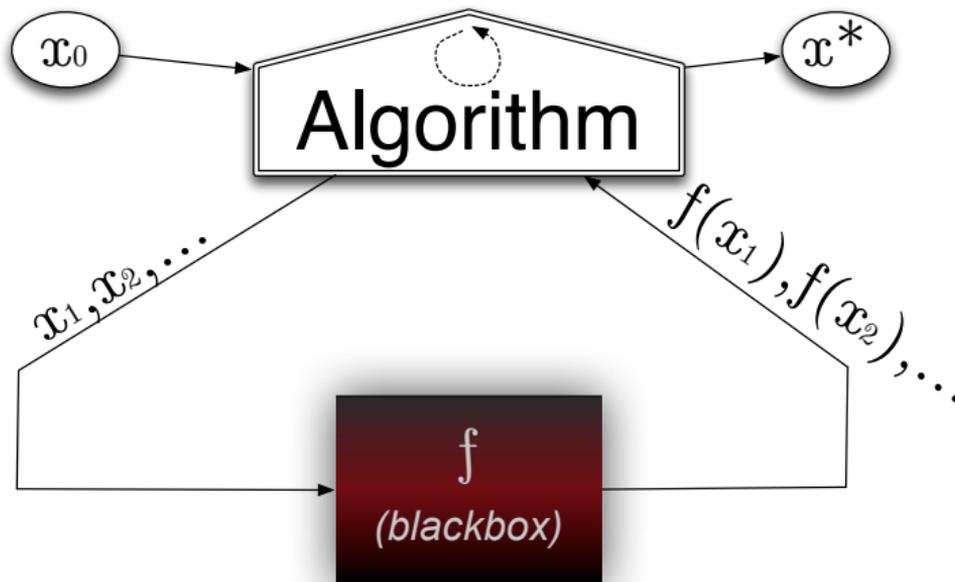
## The MADS algorithm

## Example 2: Solar thermal power plant

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## Typical setting



Unconstrained case, with one initial starting solution

## Algorithms for blackbox optimization

A method for blackbox optimization should ideally:

- ▶ Be efficient given a **limited budget of evaluations**
- ▶ Be **robust** to noise and blackbox failures
- ▶ Natively handle **general constraints**
- ▶ Deal with **multiobjective optimization**
- ▶ Deal with **integer and categorical variables**
- ▶ Easily exploit **parallelism**
- ▶ Have a publicly available **implementation**
- ▶ Have **convergence properties** ensuring first-order local optimality in the smooth case – otherwise why using it on more complicated problems?

## Families of methods

- ▶ “*Computer science*” methods:
  - ▶ Heuristics such as genetic algorithms
  - ▶ No convergence properties
  - ▶ Cost a **lot** of evaluations
  - ▶ Should be used only in **last resort** for desperate cases
  
- ▶ Statistical methods:
  - ▶ Design of experiments
  - ▶ Bayesian optimization: EGO algorithm based on **surrogates** and **expected improvement**
  - ▶ Still limited in terms of dimension
  - ▶ Does not natively handle constraints
  - ▶ Good to use these tools in conjunction with DFO methods
  
- ▶ **Derivative-Free Optimization methods (DFO)**

## DFO methods

### ▶ Model-based methods:

- ▶ Derivative-Free Trust-Region methods
- ▶ Based on quadratic models or radial-basis functions
- ▶ Use of a trust-region
- ▶ Better for { DFO \ BBO }
- ▶ Not resilient to noise and *hidden constraints*
- ▶ Not easy to parallelize

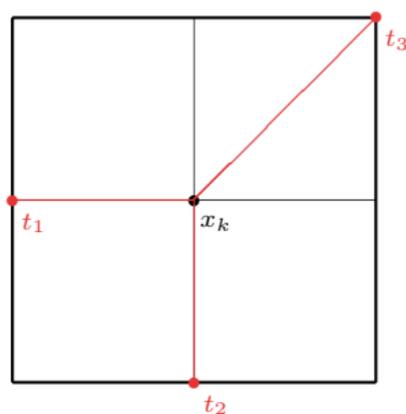
### ▶ Direct-search methods:

- ▶ Classical methods: Coordinate search, Nelder-Mead – the *other* simplex method
- ▶ Modern methods: Generalized Pattern Search, Generating Set Search, Mesh Adaptive Direct Search (MADS)

So far, the size of the instances (variables and constraints) is typically limited to  $\simeq 50$ , and we target local optimization

## MADS illustration with $n = 2$ : Poll step

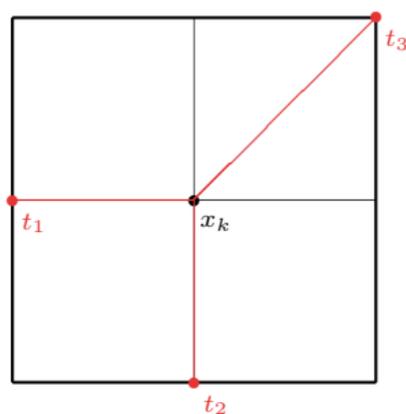
$$\delta^k = \Delta^k = 1$$



poll trial points =  $\{t_1, t_2, t_3\}$

## MADS illustration with $n = 2$ : Poll step

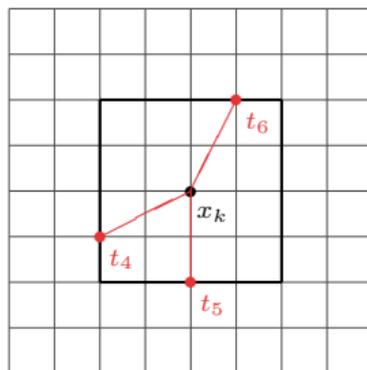
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$$\delta^{k+1} = 1/4$$

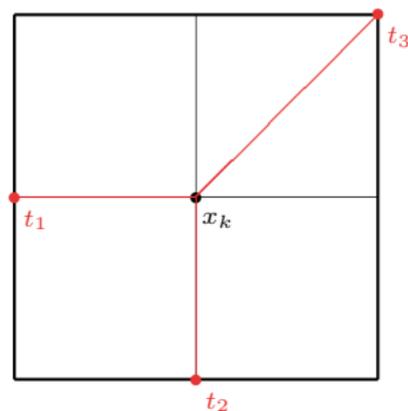
$$\Delta^{k+1} = 1/2$$



=  $\{t_4, t_5, t_6\}$

# MADS illustration with $n = 2$ : Poll step

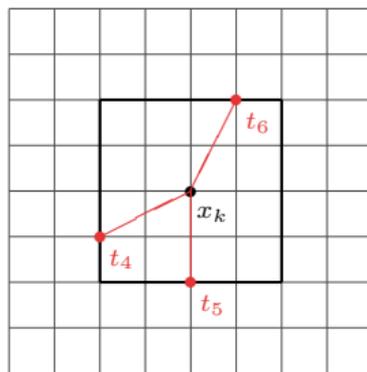
$$\delta^k = \Delta^k = 1$$



poll trial points =  $\{t_1, t_2, t_3\}$

$$\delta^{k+1} = 1/4$$

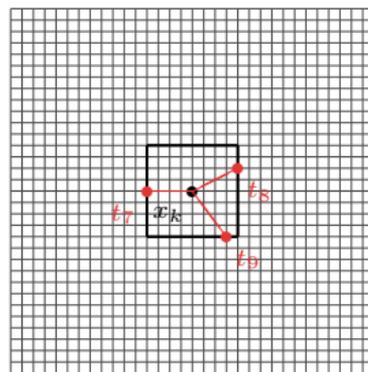
$$\Delta^{k+1} = 1/2$$



=  $\{t_4, t_5, t_6\}$

$$\delta^{k+2} = 1/16$$

$$\Delta^{k+2} = 1/4$$



=  $\{t_7, t_8, t_9\}$

**[0] Initializations**  $(x_0, \delta^0)$

**[1] Iteration**  $k$

**[1.1] Search** (flexible part)

select a finite number of **mesh** points  
 evaluate candidates opportunistically

**[1.2] Poll** (if Search failed) (“rigid” part)

construct poll set  $P_k = \{x_k + \delta^k d : d \in D_k\}$   
 sort( $P_k$ )  
 evaluate candidates opportunistically

**[2] Updates**

if success

$x_{k+1} \leftarrow$  success point  
 increase  $\delta^k$

else

$x_{k+1} \leftarrow x_k$   
 decrease  $\delta^k$

$k \leftarrow k + 1$ , stop or go to **[1]**

The MADS algorithm [Audet and Dennis, Jr., 2006]

## Special features of MADS

- ▶ **Constraints** handling with the Progressive Barrier technique [Audet and Dennis, Jr., 2009]
- ▶ **Surrogates** [Talgorn et al., 2015]
- ▶ **Categorical/Meta variables** [Audet et al., 2023]
- ▶ **Granular and discrete variables** [Audet et al., 2019]
- ▶ **Global optimization** [Audet et al., 2008a]
- ▶ **Parallelism** [Le Digabel et al., 2010, Audet et al., 2008b]
- ▶ **Multiobjective optimization** [Audet et al., 2008c, Bigeon et al., 2021]
- ▶ **Sensitivity analysis** [Audet et al., 2012]
- ▶ **Handling of stochastic blackboxes** [Alarie et al., 2021, Audet et al., 2021]

## Some MADS features

In the following slides, we focus on these MADS features:

- ▶ Constraints handling
- ▶ Use of surrogates

## Constraints – with **taxonomy** of [Le Digabel and Wild, 2015]

Domain:  $\Omega = \{x \in \mathcal{X} : c_j(x) \leq 0, j \in J\} \subset \mathbb{R}^n$

- ▶  $\mathcal{X}$  corresponds to **unrelaxable** constraints

Cannot be violated;

Example:  $x > 0$  when  $\log x$  is used inside the simulation

## Constraints – with **taxonomy** of [Le Digabel and Wild, 2015]

Domain:  $\Omega = \{x \in \mathcal{X} : c_j(x) \leq 0, j \in J\} \subset \mathbb{R}^n$

- ▶  $\mathcal{X}$  corresponds to **unrelaxable** constraints
- ▶  $c_j(x) \leq 0$ : **Relaxable** and **quantifiable** constraints

May be violated at intermediate designs

$c_j(x)$  measures the violation

Example: cost  $\leq$  budget

# Constraints – with **taxonomy** of [Le Digabel and Wild, 2015]

Domain:  $\Omega = \{x \in \mathcal{X} : c_j(x) \leq 0, j \in J\} \subset \mathbb{R}^n$

- ▶  $\mathcal{X}$  corresponds to **unrelaxable** constraints
- ▶  $c_j(x) \leq 0$ : **Relaxable** and **quantifiable** constraints
- ▶ **Hidden** constraints  
when the simulation fails, even for points in  $\Omega$

Example:

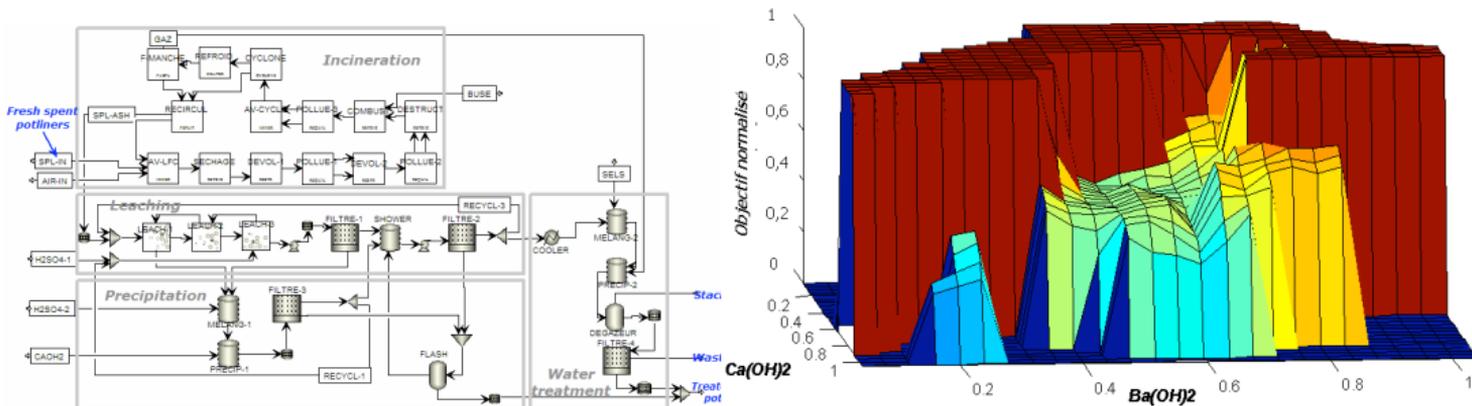
Segmentation fault  
Bus error  
ERROR 42  
DIVISION BY ZERO

## Constraints – with taxonomy of [Le Digabel and Wild, 2015]

Domain:  $\Omega = \{x \in \mathcal{X} : c_j(x) \leq 0, j \in J\} \subset \mathbb{R}^n$

- ▶  $\mathcal{X}$  corresponds to **unrelaxable** constraints
- ▶  $c_j(x) \leq 0$ : **Relaxable** and **quantifiable** constraints
- ▶ **Hidden** constraints

Example: Chemical process:



7 variables, 4 constraints. The ASPEN software fails on 43% of the calls

## Three strategies to deal with constraints

### ► Extreme barrier (EB)

Treats the problem as being unconstrained,  
by replacing the objective function  $f(x)$  by

$$f_{\Omega}(x) := \begin{cases} f(x) & \text{if } x \in \Omega \\ \infty & \text{otherwise} \end{cases}$$

The problem

$$\min_{x \in \mathbb{R}^n} f_{\Omega}(x)$$

is then solved.

Remark: this strategy can also be applied to **a priori** constraints in order to avoid the costly evaluation of  $f(x)$

## Three strategies to deal with constraints

- ▶ Extreme barrier (EB)
- ▶ Progressive barrier (PB)

Defined for relaxable and quantifiable constraints.

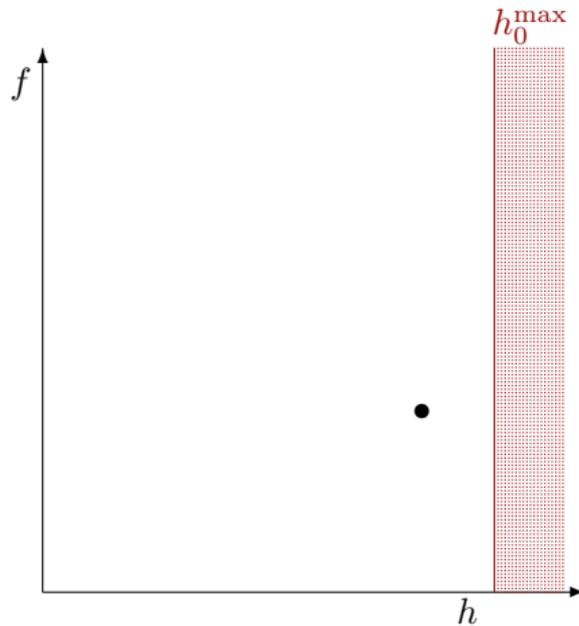
As in the filter methods of Fletcher and Leyffer, it uses the non-negative constraint violation function  $h : \mathbb{R}^n \rightarrow \mathbb{R} \cup \{\infty\}$

$$h(x) := \begin{cases} \sum_{j \in J} (\max(c_j(x), 0))^2 & \text{if } x \in \mathcal{X} \\ \infty & \text{otherwise} \end{cases}$$

At iteration  $k$ , points with  $h(x) > h_k^{\max}$  are rejected by the algorithm, and  $h_k^{\max}$  decreases toward 0 as  $k \rightarrow \infty$

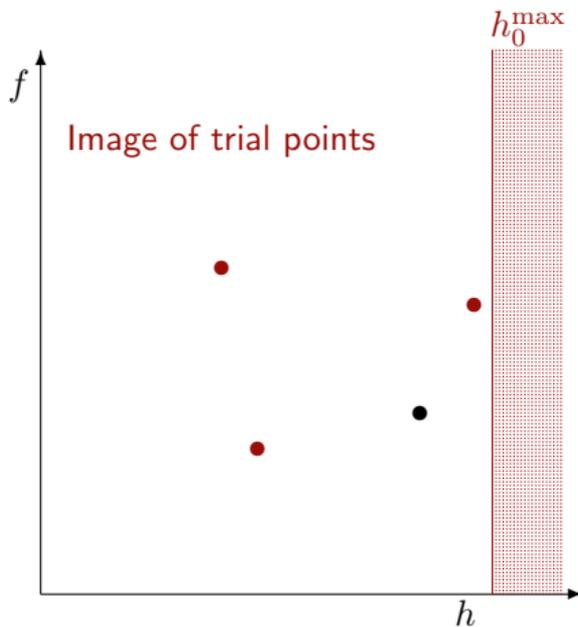
## Three strategies to deal with constraints

- ▶ Extreme barrier (EB)
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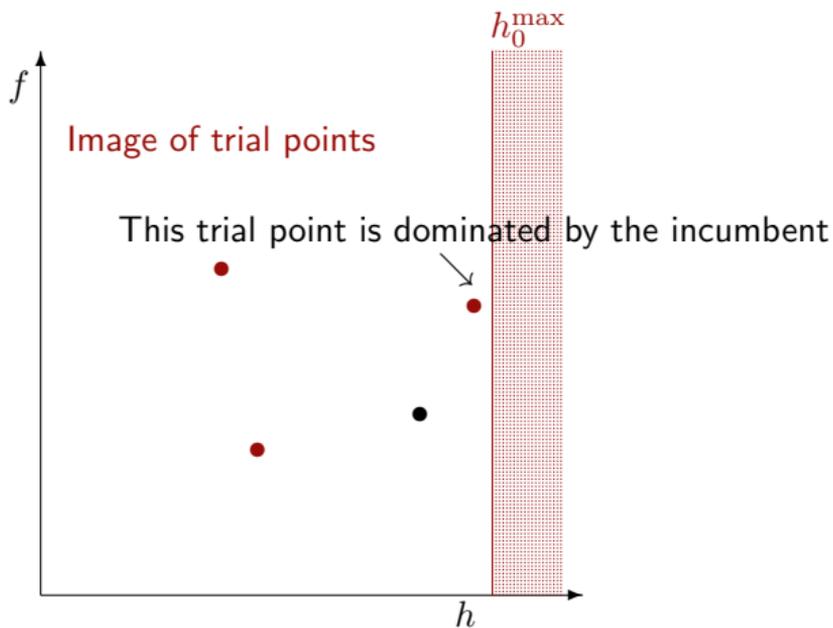
## Three strategies to deal with constraints

- ▶ Extreme barrier (EB)
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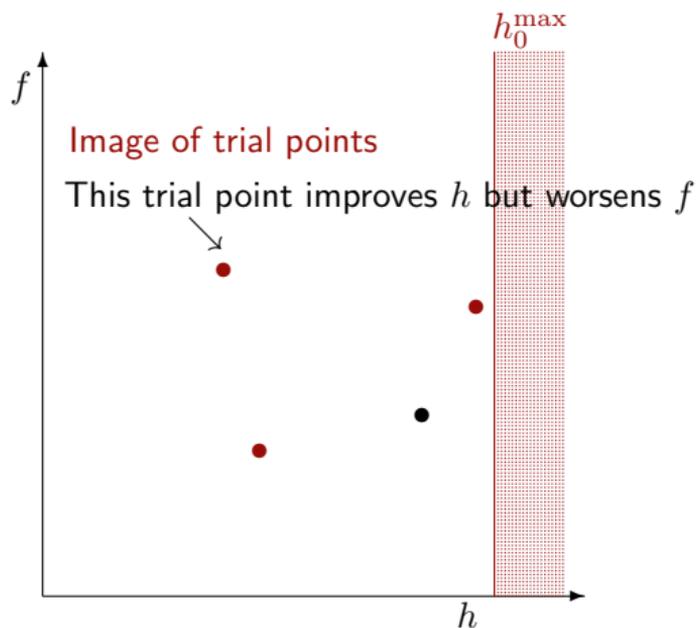
## Three strategies to deal with constraints

- ▶ Extreme barrier (EB)
- ▶ Progressive barrier (PB)



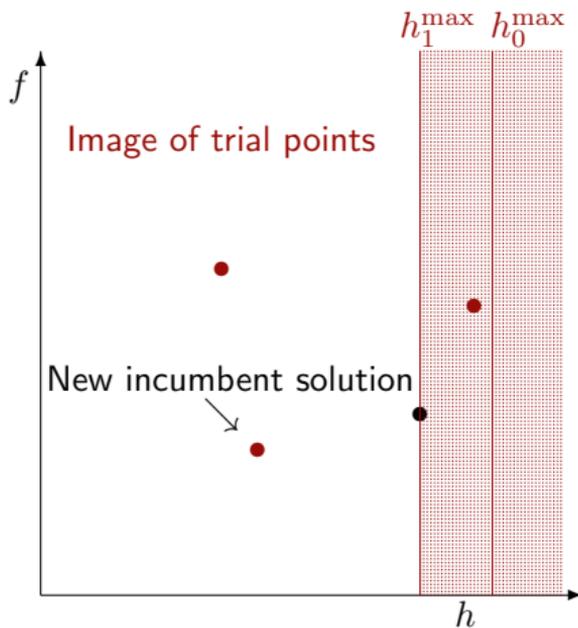
## Three strategies to deal with constraints

- ▶ Extreme barrier (EB)
- ▶ Progressive barrier (PB)



## Three strategies to deal with constraints

- ▶ Extreme barrier (EB)
- ▶ Progressive barrier (PB)



## Three strategies to deal with constraints

- ▶ Extreme barrier (EB)
- ▶ Progressive barrier (PB)
- ▶ Progressive-to-Extreme Barrier (PEB)

Initially treats a relaxable+quantifiable constraint by the progressive barrier. Then, if polling around the infeasible poll center generates a new infeasible incumbent that satisfies a constraint violated by the poll center, then that constraint moves from being treated by the progressive barrier to the extreme barrier

## Static versus dynamic surrogates

- ▶ **Static surrogate:** A cheaper model defined a priori by the user. It is used as a blackbox. Typically a simplified physics model. Variable fidelity may be considered.
- ▶ **Dynamic surrogate:** Model managed by the algorithm, based on past evaluations. It can be periodically updated.

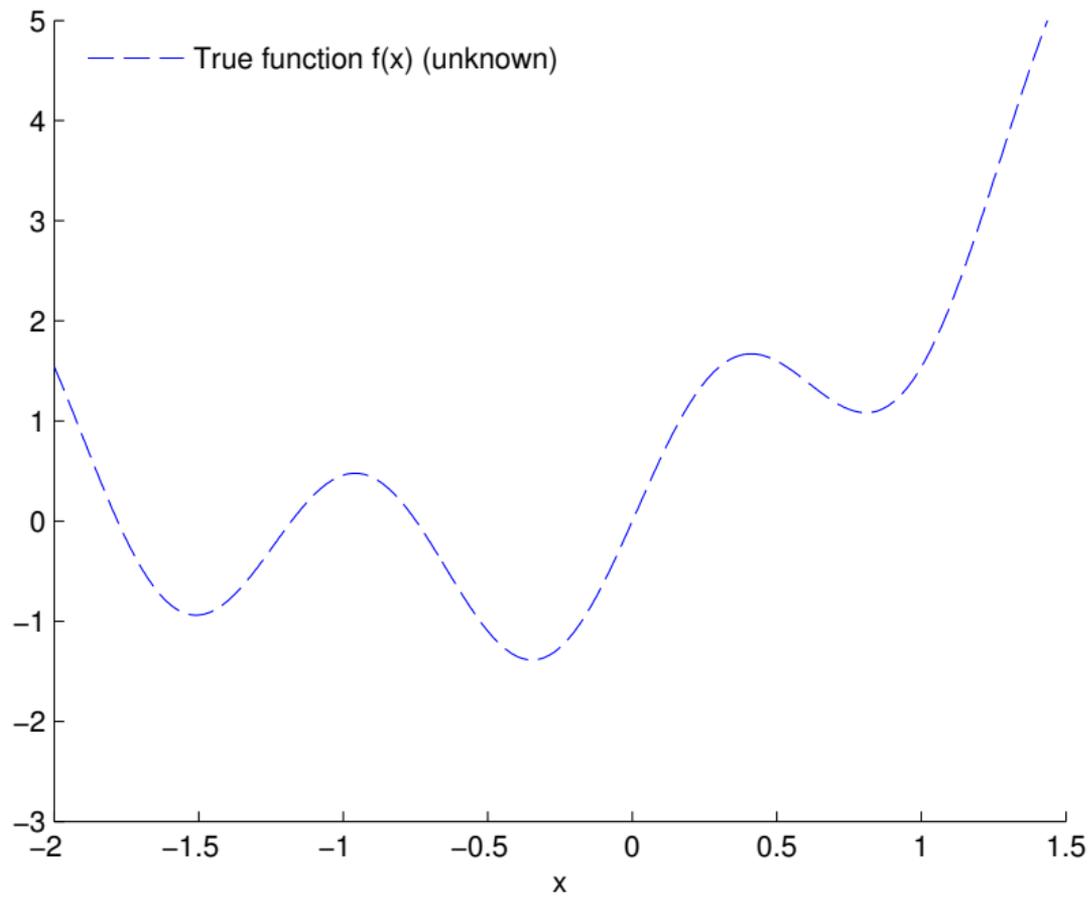
In the remaining, we focus on dynamic surrogates

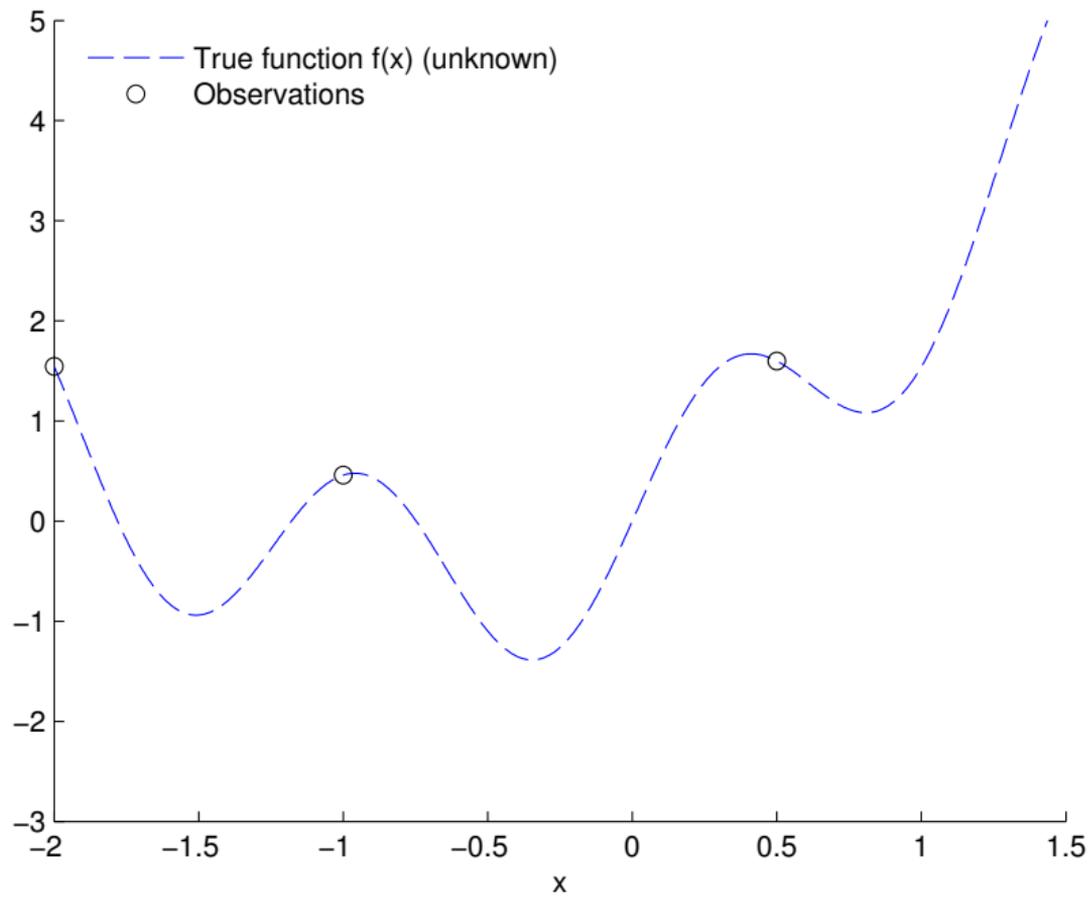
## Surrogate-assisted optimization

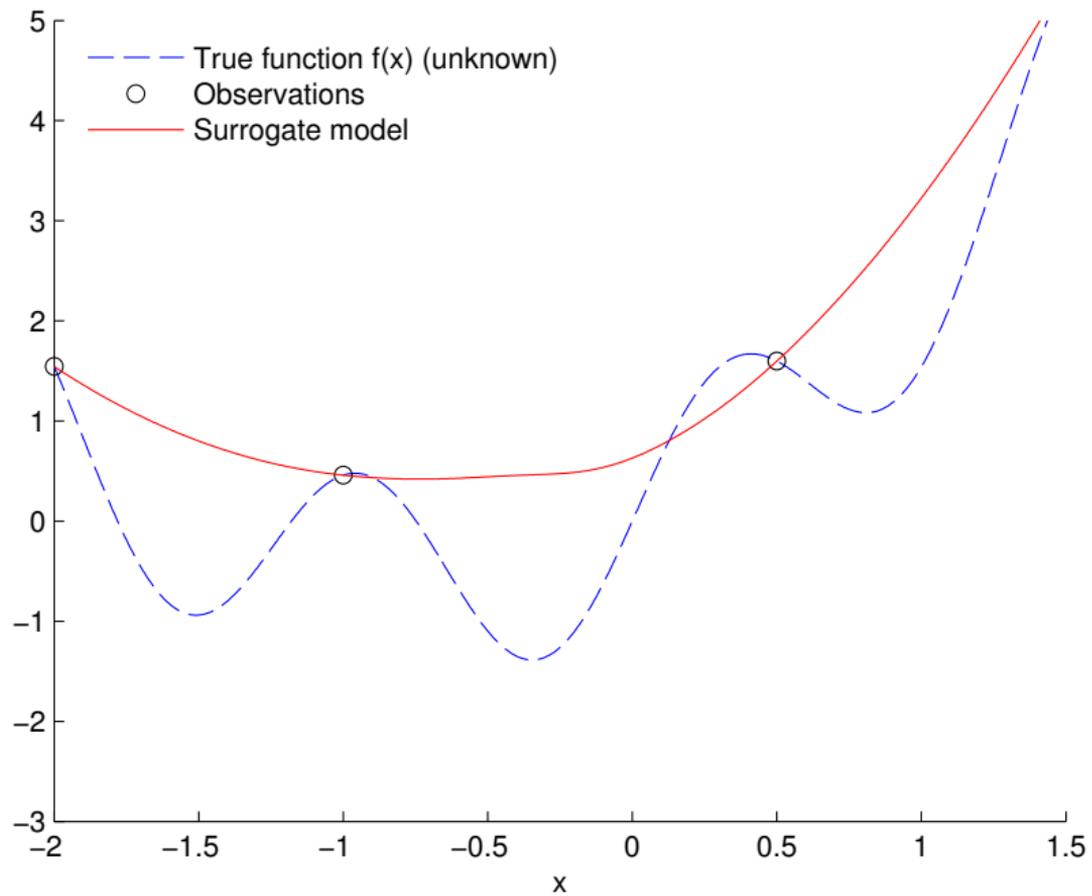
1. Use  $[\mathbf{X}, f(\mathbf{X})]$  to build a surrogate  $\hat{f}$  of the function  $f$
2. Find  $x_S \in \underset{x}{\operatorname{argmin}} \hat{f}(x)$  (or minimize another criteria such as the EI)
3. Evaluate  $f(x_S)$
4.  $\mathbf{X} \leftarrow \mathbf{X} \cup \{x_S\}$
5. Go back to **Step 1**.

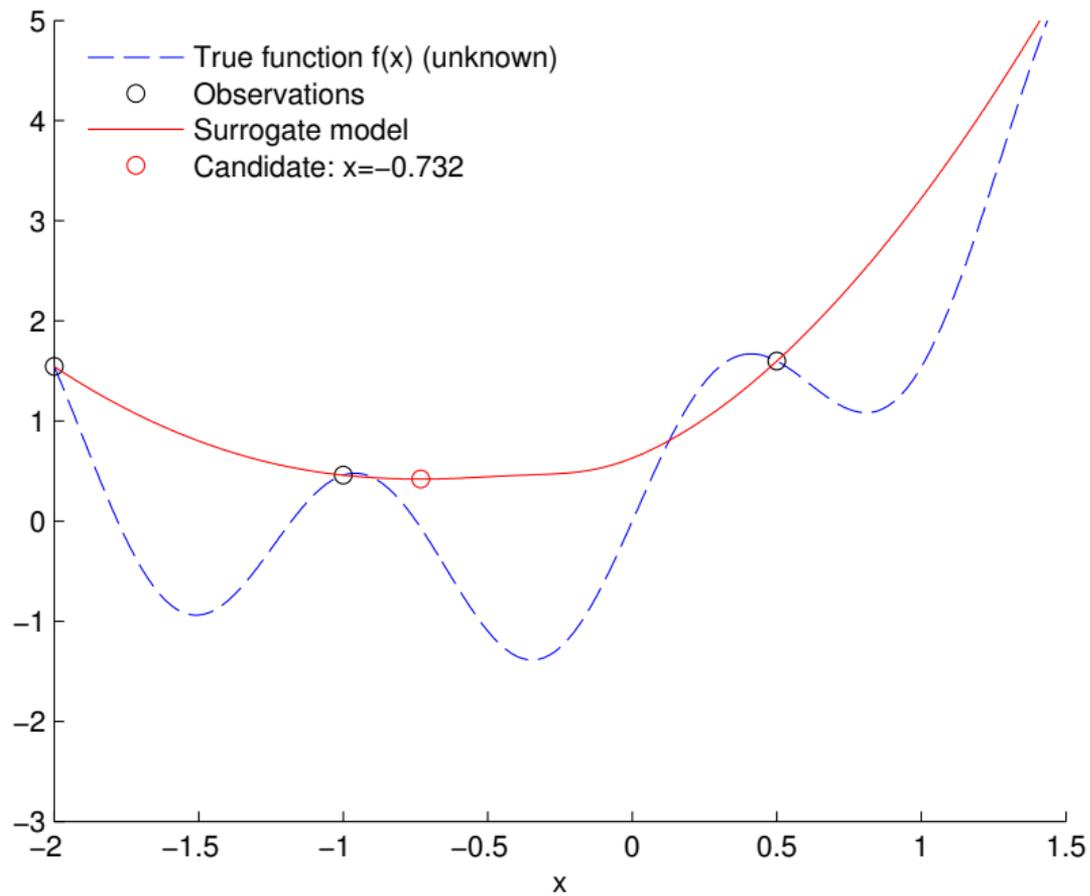
For constrained problems the same method can be used for constrained problems:

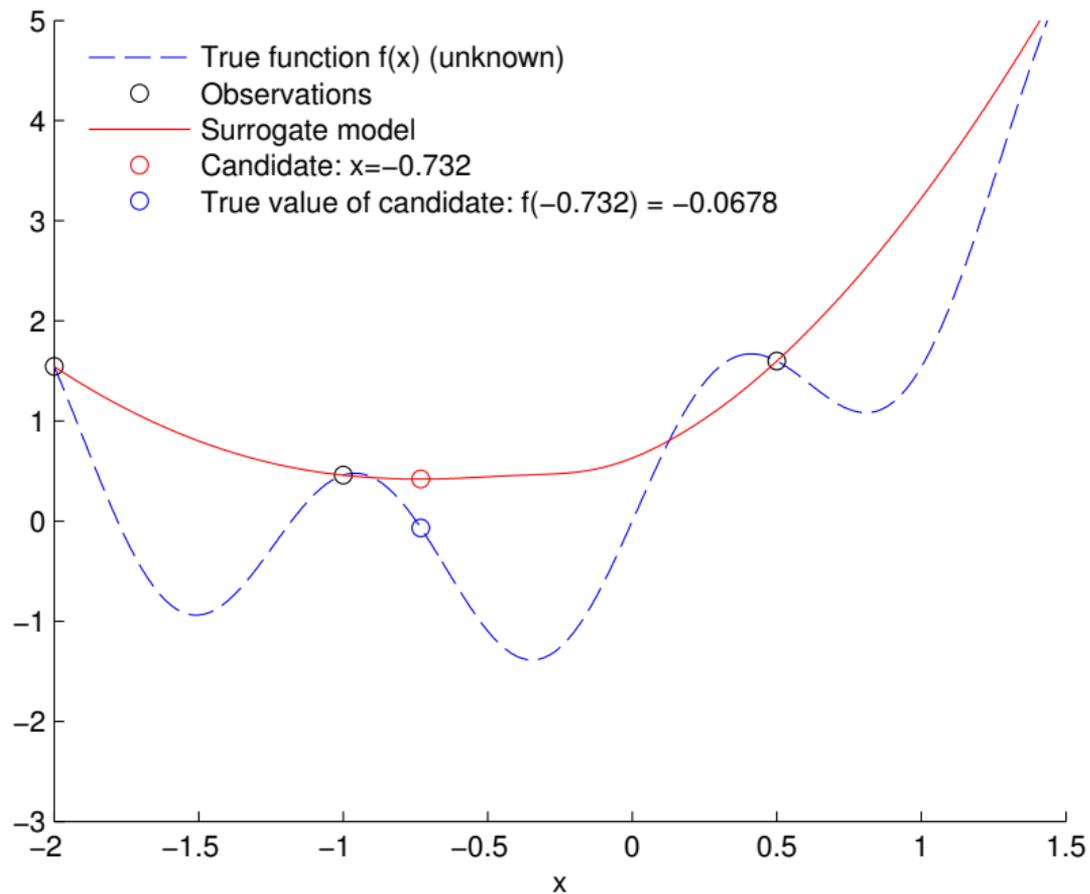
- ▶ Build the models of the constraints
- ▶  $x_S \leftarrow$  minimizer of  $\hat{f}$  subject to the constraints  $\hat{c}_j \leq 0, j = 1, 2, \dots, m$

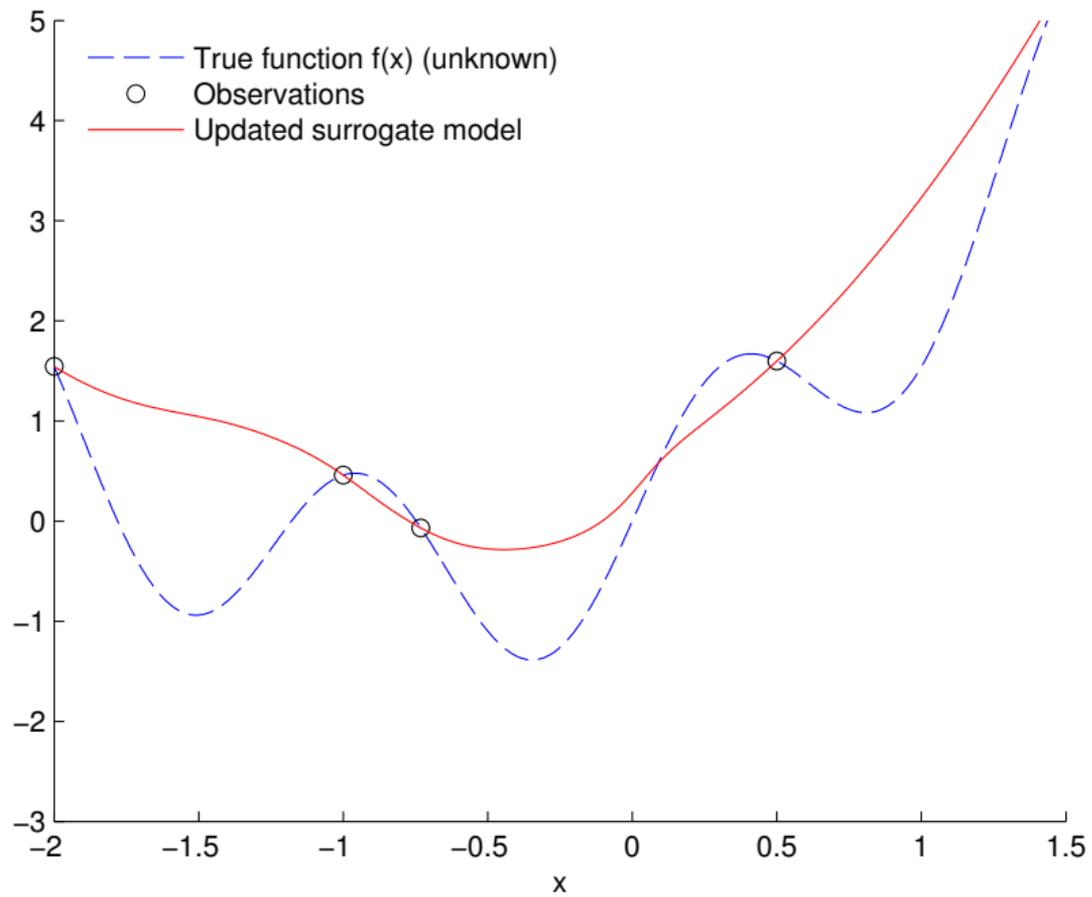


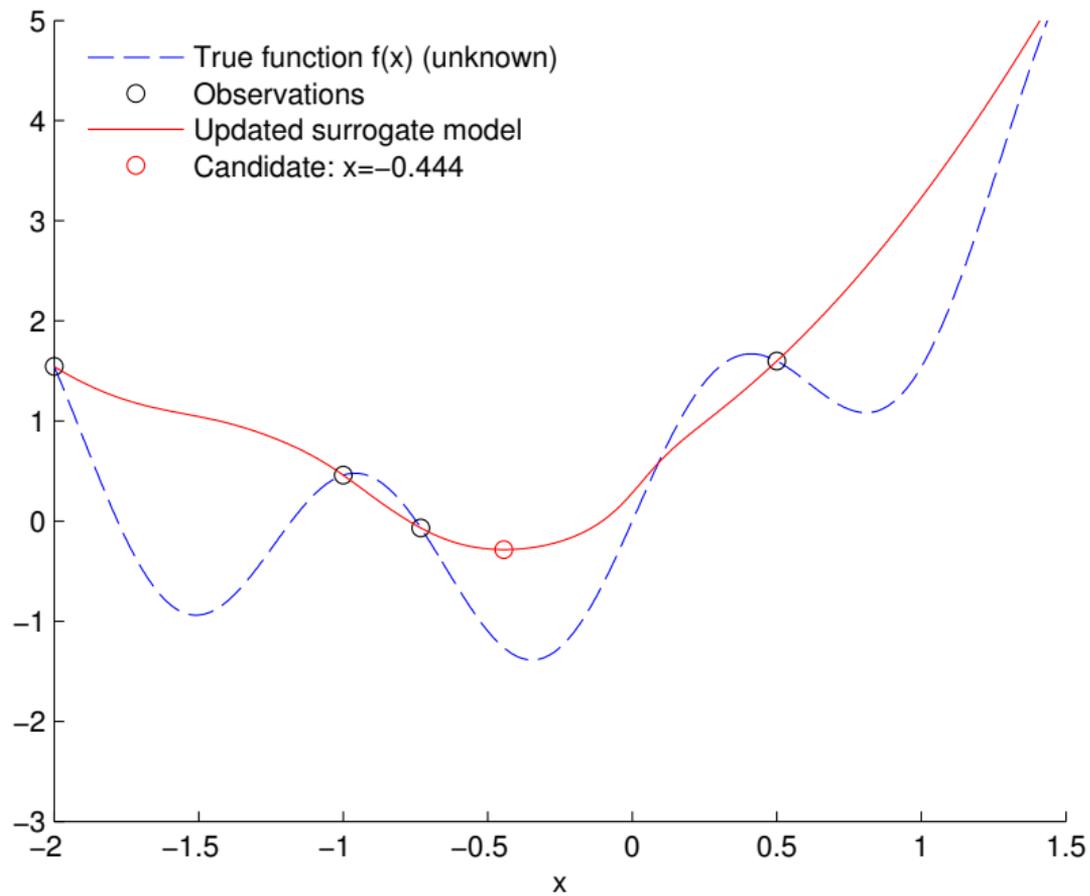


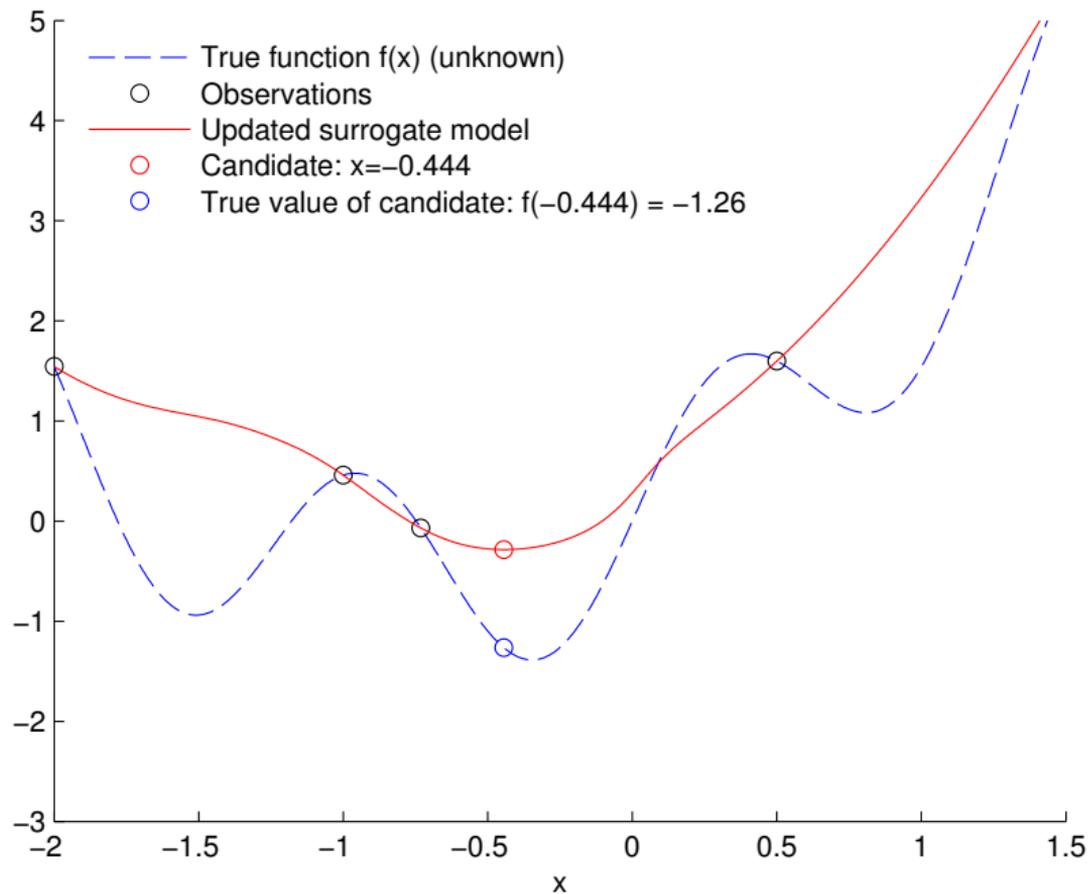


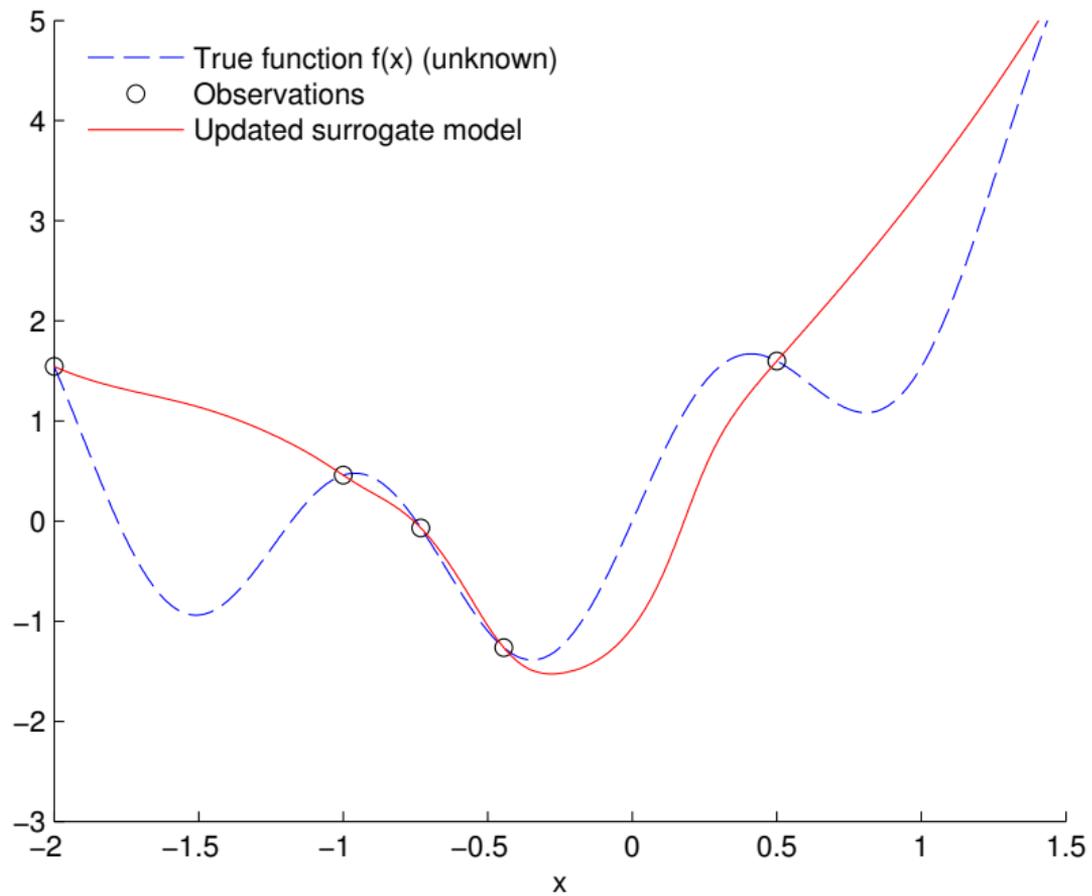


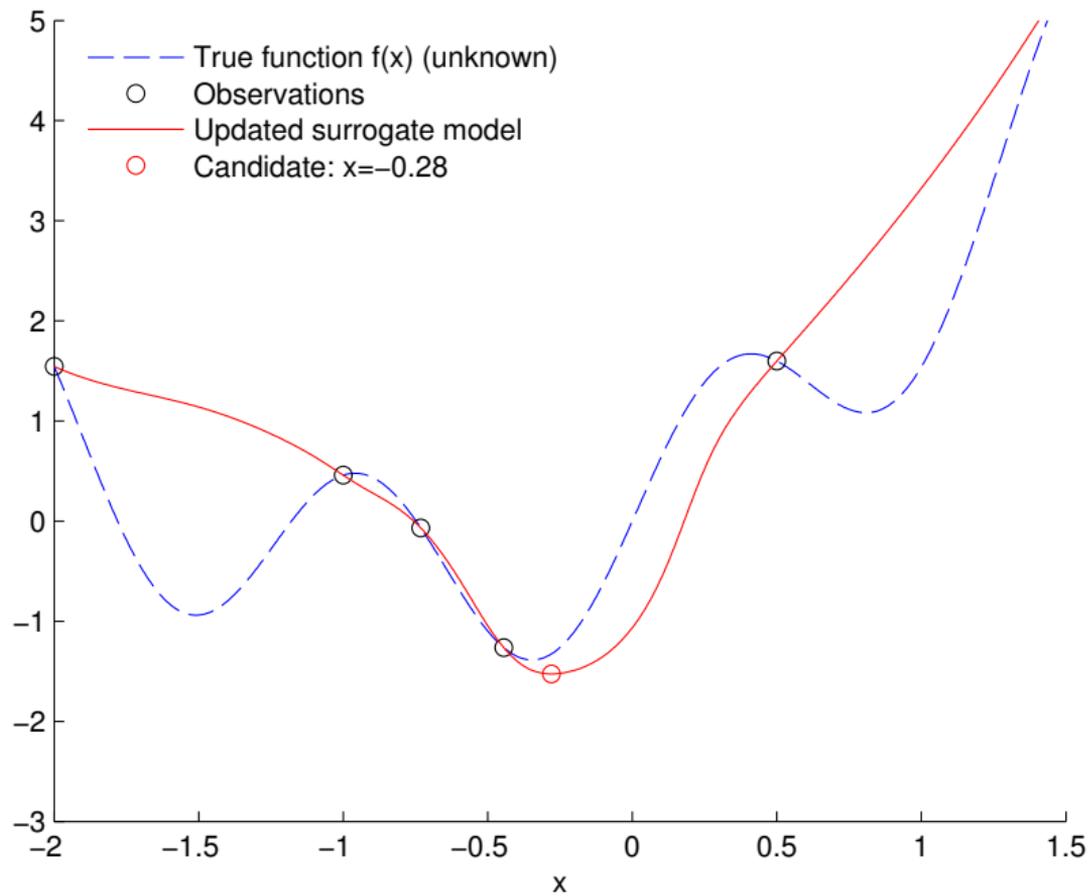


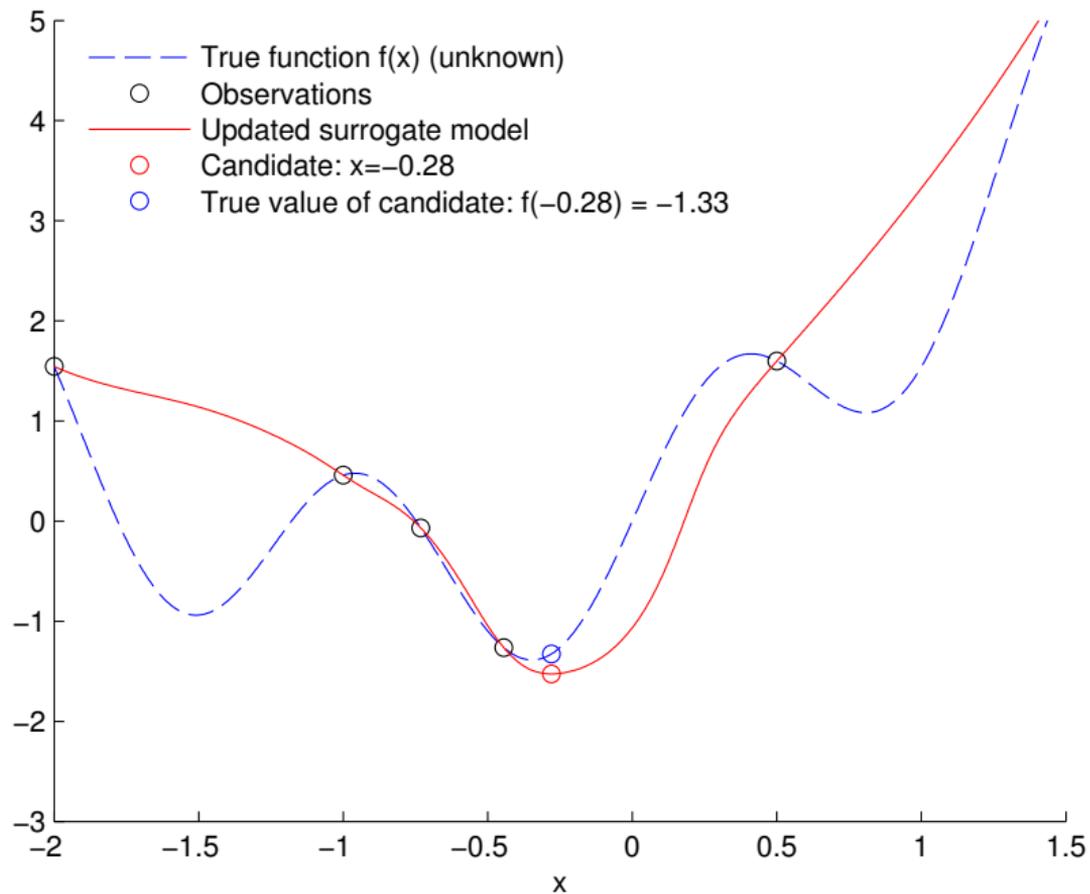


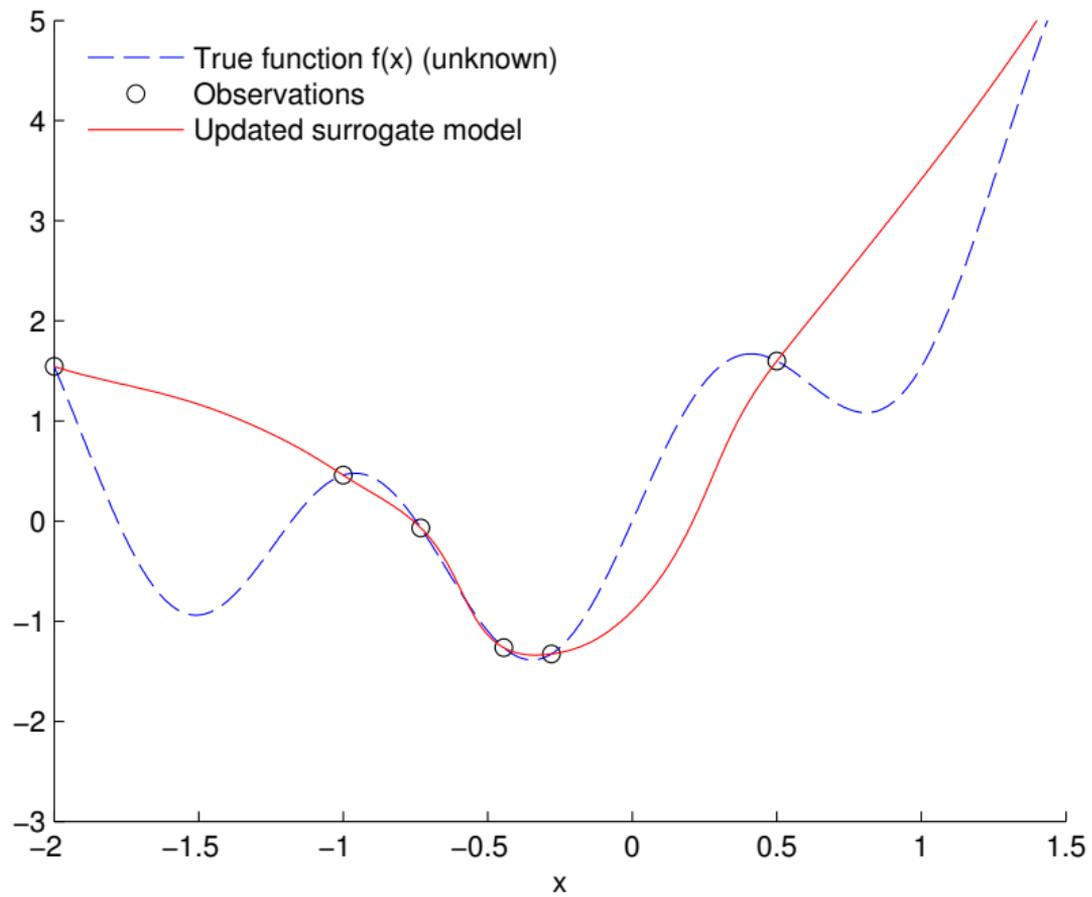


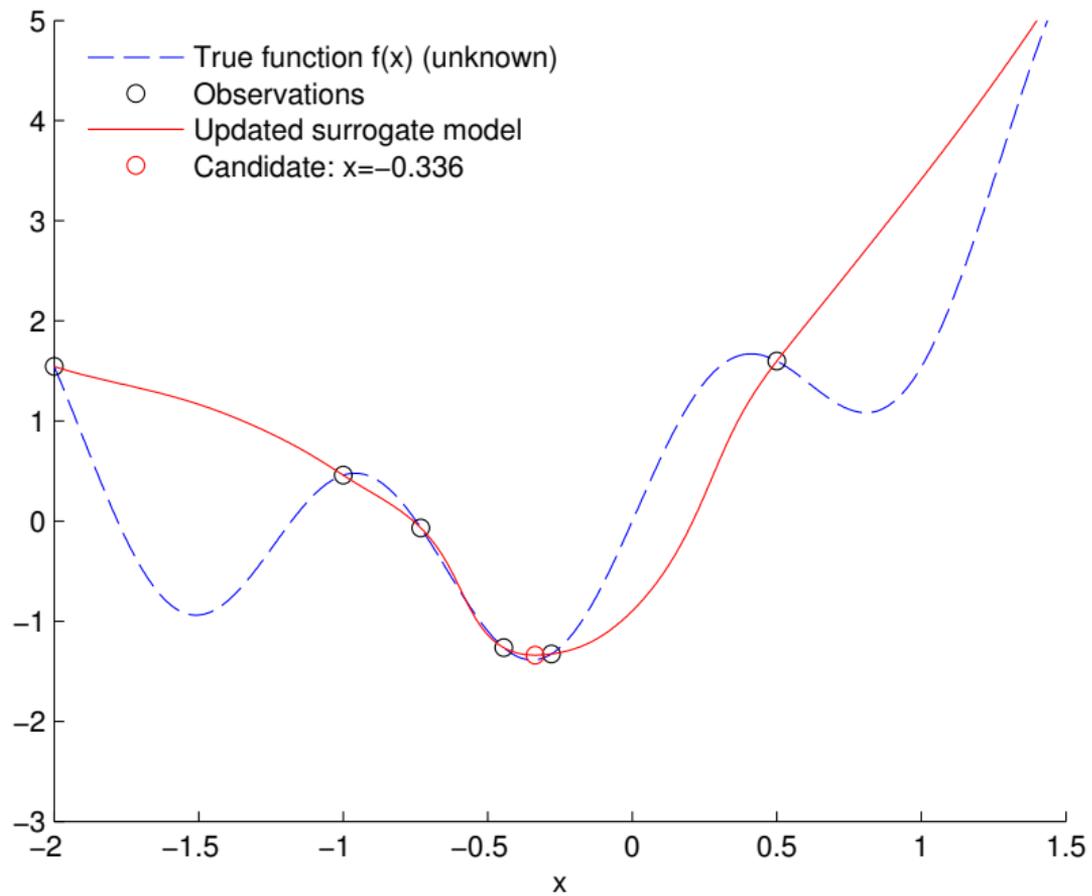


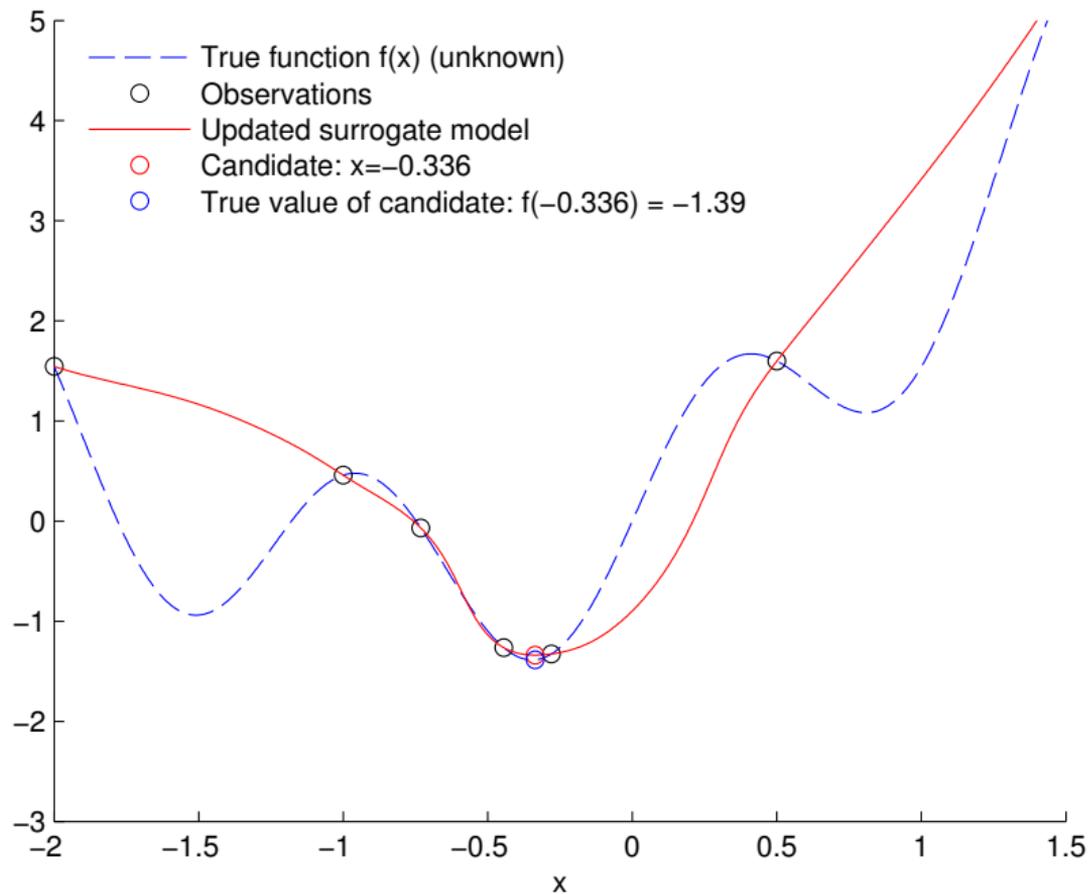


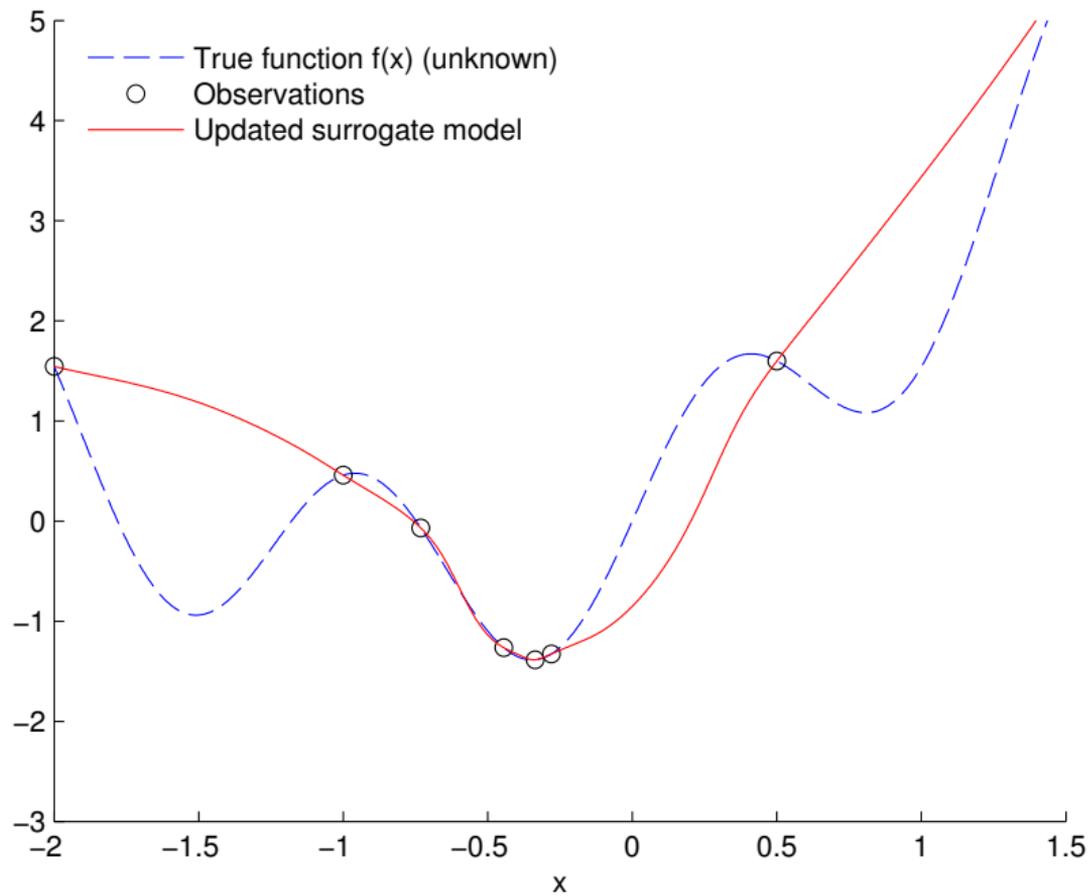


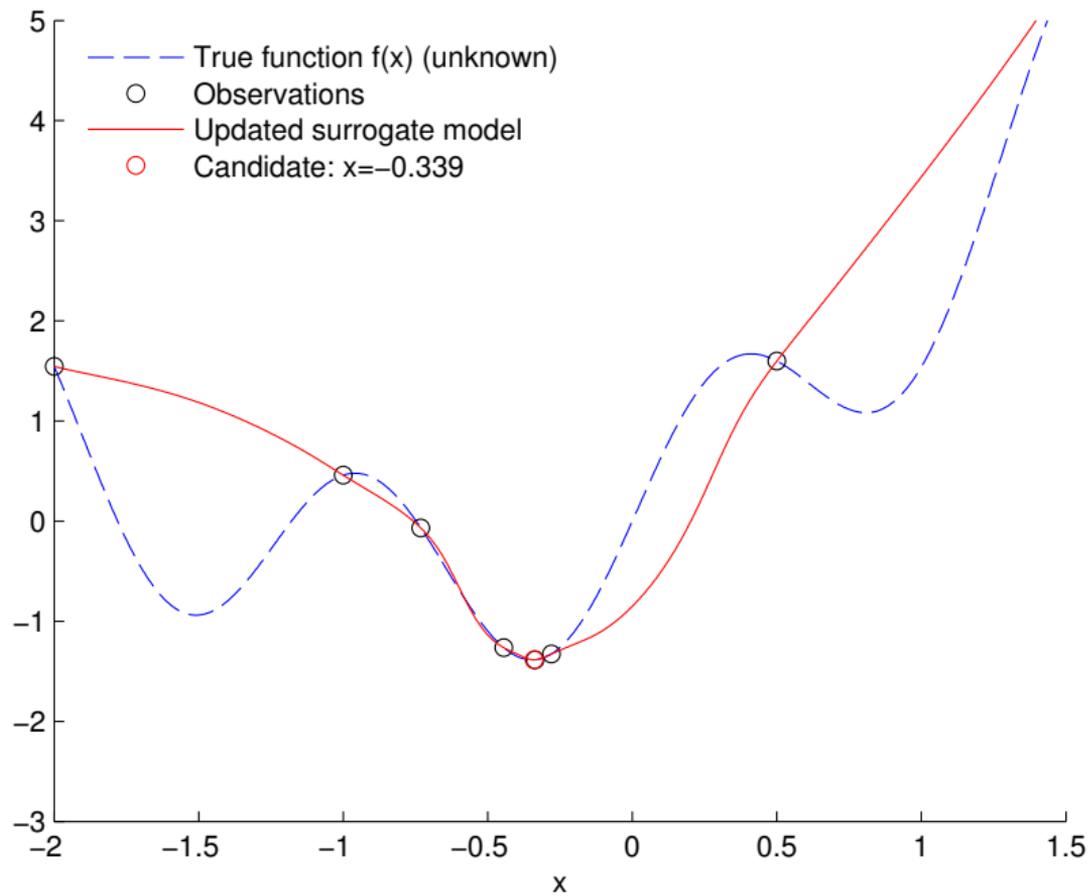












# Surrogate-assisted optimization in MADS

## 1. Initialization:

- ▶ Initial design ( $x_0$ )
- ▶ Initial mesh and poll sizes ( $\delta^0, \Delta^0$ )

## 2. Search

- ▶ Build the **surrogates**  $\hat{f}$  and  $\{\hat{c}_j\}_{j=1,2,\dots,m}$
- ▶  $\mathbf{x}_S \leftarrow$  solution of the surrogate problem, projected on the current mesh
- ▶ If  $\mathbf{x}_S$  is a success, repeat the search

## 3. Poll

- ▶ Construct the poll candidates
- ▶ Use the **surrogates** to order the poll candidates
- ▶ Evaluate the poll candidates *opportunistically*

## 4. If no stopping criteria is met, go back to [Step 2](#).

## What is a good model for surrogate-assisted optimization

- ▶ Good model of the objective  $f$ : respects the **order** between two candidates:

$$f(\mathbf{x}) \leq f(\mathbf{x}') \Leftrightarrow \hat{f}(\mathbf{x}) \leq \hat{f}(\mathbf{x}') \text{ for all } \mathbf{x}, \mathbf{x}' \in \mathcal{X}$$

- ▶ Good model of a constraint  $c_j$ : respects the **sign** of the function:

$$c_j(\mathbf{x}) \leq 0 \Leftrightarrow \hat{c}_j(\mathbf{x}) \leq 0 \text{ for all } \mathbf{x} \in \mathcal{X}$$

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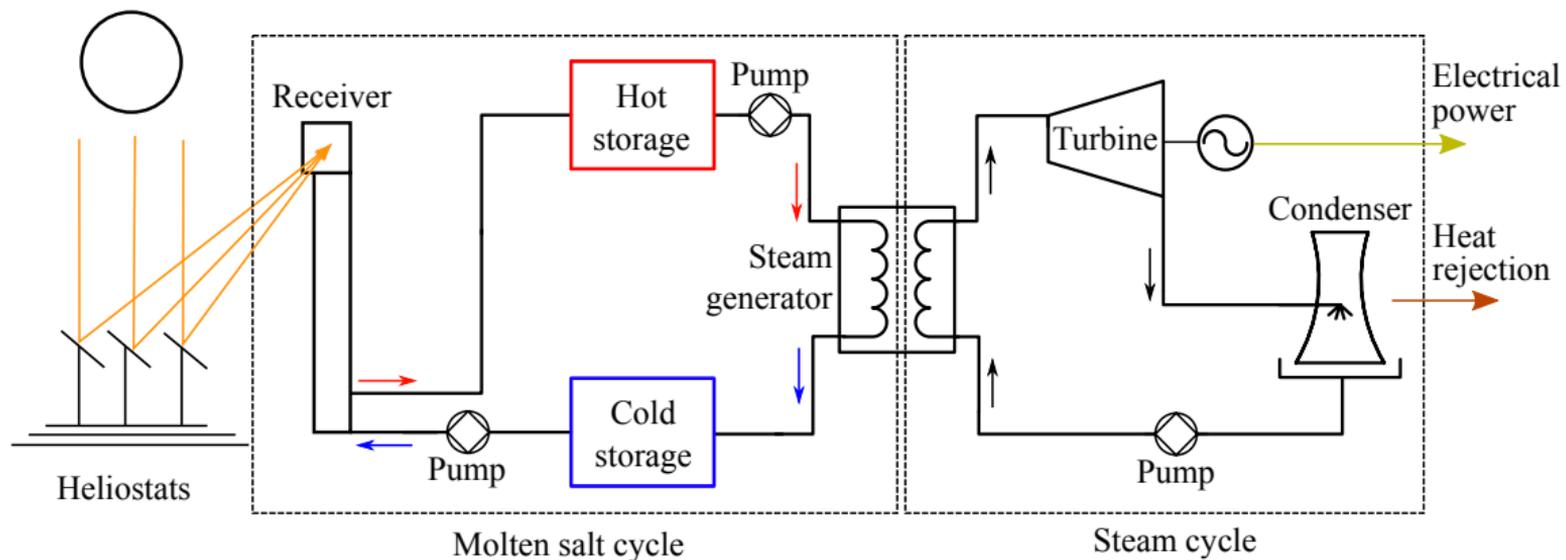
## CSP power plant with molten salt thermal energy storage

- ▶ A large number of mirrors (**heliostats**) reflects solar radiation on a receiver at the top of a tower
- ▶ The heat collected from the concentrated solar flux is removed from the receiver by a stream of molten salt
- ▶ Hot molten salt is then used to feed thermal power to a conventional power block
- ▶ The photo shows the Thémis CSP power plant, the first built with this design



Source: [https://commons.wikimedia.org/wiki/File:Themis\\_2.jpg](https://commons.wikimedia.org/wiki/File:Themis_2.jpg)

# System dynamics



## Ten instances

Instance	# of variables		$n$	# of obj. $p$	# of constraints		$m$	# of stoch. outputs (obj. or constr.)	Static surrogate
	cont.	discr. (cat.)			simu.	a priori (lin.)			
solar1	8	1 (0)	9	1	2	3 (2)	5	1	no
solar2 <sup>1</sup>	12	2 (0)	14	1	9	4 (2)	13	3	yes
solar3	17	3 (1)	20	1	8	5 (3)	13	5	yes
solar4	22	7 (1)	29	1	9	7 (5)	16	6	yes
solar5	14	6 (1)	20	1	8	4 (3)	12	0	no
solar6	5	0 (0)	5	1	6	0 (0)	6	0	no
solar7	6	1 (0)	7	1	4	2 (1)	6	3	yes
solar8	11	2 (0)	13	2	4	5 (3)	9	3	yes
solar9	22	7 (1)	29	2	10	7 (5)	17	6	yes
solar10 <sup>2</sup>	5	0 (0)	5	1	0	0 (0)	0	0	yes

<sup>1</sup>analytic objective

<sup>2</sup>unconstrained

## Features for BBO benchmarking

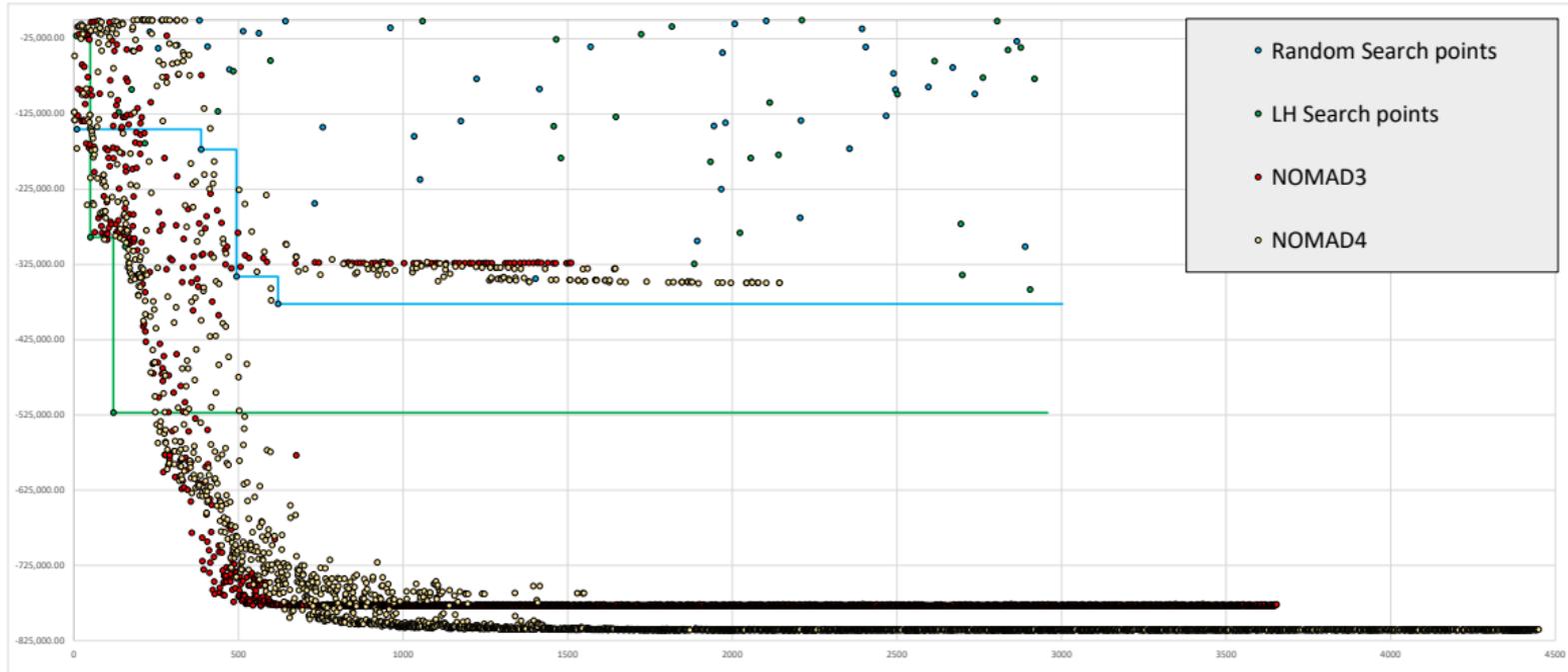
- ▶ Several numerical methods: real-world blackbox
- ▶ Reproducibility accros all platforms
- ▶ Continuous and discrete variables
- ▶ Different types of constraints (quantifiable, relaxable, a priori, hidden)
- ▶ Stochastic and deterministic outputs
- ▶ Static surrogates with variable fidelity
- ▶ Number of replications is controlable

## Feasibility with sampling and NOMAD

Instance	LH search (10k points)			NOMAD3			
	satisf. ap	constr.	feas. pts	satisf. ap	constr.	feas. pts	number of eval.
solar1	30%		0.35%	96%		74%	3,792
solar2	0%		0%	97%		0%	1,635
solar3	0.49%		0%	99%		9%	30,525
solar4	0%		0%	83%		0%	44,303
solar5	0%		0%	83%		59%	3,405
solar6	90%		5%	99%		0%	3,539
solar7	2%		1%	74%		72%	2,224
solar8	1%		0.03%				
solar9	1%		0%				

there has been no violation of **hidden** constraints during the construction of this table

# Optimization on solar1



## Introduction

### Example 1: Aircraft takeoff trajectories

### The MADS algorithm

### Example 2: Solar thermal power plant

## The NOMAD software package

## References

## NOMAD (Nonlinear Optimization with MADS)

- ▶ C++ implementation of the MADS algorithm [Audet and Dennis, Jr., 2006]
- ▶ Standard C++. Runs on Linux, Mac OS X and Windows
- ▶ Parallel versions
- ▶ MATLAB versions; Multiple interfaces (Python, Julia, etc.)
- ▶ Open and free – LGPL license
- ▶ Download at <https://www.gerad.ca/nomad>
- ▶ Support at [nomad@gerad.ca](mailto:nomad@gerad.ca)
  
- ▶ Related articles in TOMS [Le Digabel, 2011] and [Audet et al., 2022]



## Main functionalities (1/2)

- ▶ Single or biobjective optimization
- ▶ Variables:
  - ▶ Continuous, integer, binary, categorical, granular
  - ▶ Periodic
  - ▶ Fixed
  - ▶ Groups of variables
- ▶ Searches:
  - ▶ Latin-Hypercube
  - ▶ Variable Neighborhood Search
  - ▶ Nelder-Mead Search
  - ▶ Quadratic models
  - ▶ Statistical surrogates
  - ▶ User search

## Main functionalities (2/2)

- ▶ Constraints treated with 4 different methods:
    - ▶ Progressive Barrier (default)
    - ▶ Extreme Barrier
    - ▶ Progressive-to-Extreme Barrier
    - ▶ Filter method
  - ▶ Several direction types:
    - ▶ Coordinate directions
    - ▶ LT-MADS
    - ▶ OrthoMADS
    - ▶ Hybrid combinations
  - ▶ Sensitivity analysis
- default values for all parameters
- all items correspond to published or submitted papers

## Blackbox conception (batch mode)

- ▶ Command-line program that takes in argument a file containing  $x$ , and displays the values of  $f(x)$  and the  $c_j(x)$ 's
- ▶ Can be coded in any language
- ▶ Typically: `> bb.exe x.txt` displays `f c1 c2` (objective and two constraints)

# Run NOMAD

```
> nomad parameters.txt
```

```
[iota ~/Desktop/2018_UQAC_NOMAD/demo_NOMAD/mac] > ../nomad.3.8.1/bin/nomad parameters.txt

NOMAD - version 3.8.1 has been created by {
  Charles Audet      - Ecole Polytechnique de Montreal
  Sebastien Le Digabel - Ecole Polytechnique de Montreal
  Christophe Tribes  - Ecole Polytechnique de Montreal
}

The copyright of NOMAD - version 3.8.1 is owned by {
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  Christophe Tribes   - Ecole Polytechnique de Montreal
}

NOMAD v3 has been funded by AFOSR, Exxon Mobil, Hydro Québec, Rio Tinto and
IVADO.

NOMAD v3 is a new version of NOMAD v1 and v2. NOMAD v1 and v2 were created
and developed by Mark Abramson, Charles Audet, Gilles Couture, and John E.
Dennis Jr., and were funded by AFOSR and Exxon Mobil.

License : '$NOMAD_HOME/src/lgpl.txt'
User guide: '$NOMAD_HOME/doc/user_guide.pdf'
Examples : '$NOMAD_HOME/examples'
Tools : '$NOMAD_HOME/tools'

Please report bugs to nomad@gerad.ca

Seed: 0

MADS run {

  BBE   OBJ

  4     0.0000000000
  21    -1.0000000000
  23    -3.0000000000
  51    -4.0000000000
  563   -4.0000000000

} end of run (mesh size reached NOMAD precision)

blackbox evaluations : 563
best infeasible solution (min. violation): ( 1.000000013 1.000000048 0.9999999797 0.999999992 -4 ) h=1.10134e-13 f=-4
best feasible solution : ( 1 1 1 1 -4 ) h=0 f=-4
```

## Introduction

### Example 1: Aircraft takeoff trajectories

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### Example 2: Solar thermal power plant

### The NOMAD software package

## References

## Summary

- ▶ **Blackbox optimization** motivated by industrial applications
- ▶ Algorithmic features backed by mathematical **convergence analyses** and published in **optimization journals**
- ▶ **NOMAD**: Software package implementing **MADS**
- ▶ Open source; **LGPL** license
- ▶ **Features**: Constraints, biobjective, global optimization, surrogates, several types of variables, parallelism
- ▶ **Fast support** at [nomad@gerad.ca](mailto:nomad@gerad.ca)
- ▶ NOMAD has become a **baseline** for benchmarking DFO algorithms

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