Random subspaces and expected decrease in derivative-free optimization

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Roadmap

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1. Direct search
2. Reduced subspace approach
3. More on 1D subspaces

Introductory assumptions and definitions

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

Assumptions

- f bounded below;
- f continuously differentiable (nonconvex).

Blackbox/Derivative-free setup

- **Derivatives unavailable for algorithmic use.**
- Only access to values of f.
- Important paradigm (cf Anne Auger's plenary).

Complexity in blackbox optimization

My goal as a derivative-free/blackbox optimizer

Develop algorithms with controlled

- Number of calls to f;
- Dependency on n.

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Given $\epsilon \in (0,1)$ and, bound the number of function evaluations needed by a method to reach $\boldsymbol{x}$ such that

$$\|\nabla f(\boldsymbol{x})\| \leq \epsilon,$$

deterministically or in expectation/probability.

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Focus: dependency w.r.t. n.

DFO algorithms

Main algorithmic families

- Direct search: Explore the space through selected directions.
- Model based: Build a surrogate for the objective function.

Choosing a family for a Friday talk

- Direct search simpler to explain.
- **All results have a model-based counterpart**.

A (simplified) direct-search framework

Inputs: $\boldsymbol{x}_0 \in \mathbb{R}^n$, $\delta_0 > 0$.

Iteration k: Given $(\boldsymbol{x}_k, \delta_k)$,

- Choose a set $\mathcal{D}_k \subset \mathbb{R}^n$ of m vectors.
- If $\exists\ \boldsymbol{d}_k \in \mathcal{D}_k$ such that

$$f(\boldsymbol{x}_k + \delta_k\, \boldsymbol{d}_k) < f(\boldsymbol{x}_k) - \delta_k^2 \|\boldsymbol{d}_k\|^2$$

  set $\boldsymbol{x}_{k+1} := \boldsymbol{x}_k + \delta_k \boldsymbol{d}_k$, $\delta_{k+1} := 2\delta_k$.
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Which vectors should we use?

Choosing $\mathcal{D}_k$

A measure of set quality

The set $\mathcal{D}_k$ is called κ-descent for f at $\boldsymbol{x}_k$ if

$$\max_{\boldsymbol{d} \in \mathcal{D}_k} \frac{-\boldsymbol{d}^{\mathrm{T}} \nabla f(\boldsymbol{x}_k)}{\|\boldsymbol{d}\| \|\nabla f(\boldsymbol{x}_k)\|} \geq \kappa \in (0, 1].$$

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- Guaranteed when $\mathcal{D}_k$ is a Positive Spanning Set (PSS);
- $\mathcal{D}_k$ PSS $\Rightarrow |\mathcal{D}_k| \geq n+1$;
- Ex) $\mathcal{D}_\oplus := \{\boldsymbol{e}_1,\dots,\boldsymbol{e}_n,\text{-}\boldsymbol{e}_1,\dots,\text{-}\boldsymbol{e}_n\}$ is always $\frac{1}{\sqrt{n}}$-descent.

Complexity of deterministic direct search

Assumption: For every k, $\mathcal{D}_k$ is κ-descent and contains m unit directions.

Theorem (Vicente '12)

Let $\epsilon \in (0,1)$ and N_ϵ be the number of function evaluations needed to reach $\boldsymbol{x}_k$ such that $\|\nabla f(\boldsymbol{x}_k)\| \le \epsilon$. Then,

$$N_\epsilon \ \le \ \mathcal{O}\left(m\,\kappa^{-2}\,\epsilon^{-2}\right).$$

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- Unit norm can be replaced by bounded norm.
- Choosing $\mathcal{D}_k = \mathcal{D}_\oplus$, one has $\kappa = \frac{1}{\sqrt{n}}$, $m = 2n$, and the bound becomes

$$N_\epsilon \;\le\; \mathcal{O}\left(n^2\,\epsilon^{-2}\right).$$

$\Rightarrow$**Best possible dependency** w.r.t. n for deterministic direct-search algorithms.

Randomizing direct search

Classical direct search

- Set $\mathcal{D}_k \subset \mathbb{R}^n$, $|\mathcal{D}_k| = m$, $\mathrm{cm}(\mathcal{D}_k) \geq \kappa$;
- Complexity:

$$\mathcal{O}(m\kappa^{-2}\,\epsilon^{-2}).$$

  - m depends on n $(m \geq n+1)$.
  - κ depends on n (approximate $\nabla f(\boldsymbol{x}_k) \in \mathbb{R}^n$).

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My original thought

- Generate directions in random subspaces of $\mathbb{R}^n$;
- Use results from dimensionality reduction;
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- Remove all dependencies on n!

Spoiler alert: You can only *reduce* the dependency on n.

What can you do?

Our approach

- Consider a random subspace of dimension $r \leq n$;
- Use a PSS to approximate the projected gradient in the subspace;
- Guarantee sufficient gradient information **in probability**.

What it brings us

- Use random directions.
- Possibly less than n.
- Possibly **unbounded**.

Not the only game in town (1/2)

Probabilistic descent (Gratton et al '15)

- Use directions $[\boldsymbol{d} \ -\boldsymbol{d}]$ with $\boldsymbol{d} \sim \mathcal{U}(\mathbb{S}^{n-1})$.
- Complexity improves from $\mathcal{O}(n^2\epsilon^{-2})$ to $\mathcal{O}(n\epsilon^{-2})$ $(m = 2)$.
- Limited to one distribution.

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Gaussian smoothing approach: Draw $\boldsymbol{d} \sim \mathcal{N}(0, \boldsymbol{I})$ and use

$$\frac{f(\boldsymbol{x}+\delta\boldsymbol{d}) - f(\boldsymbol{x})}{\delta}\boldsymbol{d} \quad \text{or} \quad \frac{f(\boldsymbol{x}+\delta\boldsymbol{d}) - f(\boldsymbol{x}-\delta\boldsymbol{d})}{\delta}\boldsymbol{d}.$$

Random gradient-free method (Nesterov and Spokoiny 2017),
Stochastic three-point method (Bergou et al, 2020).

- Also achieve $\mathcal{O}(n\epsilon^{-2})$ bound.
- Use one-dimensional subspace based on Gaussian vectors.
- Use fixed or decreasing stepsizes.

Not the only game in town (2/2)

Zeroth-order (Kozak et al '21, '22)

- Estimate directional derivatives directly.
- Use orthogonal random directions.
- Complexity results for convex/PL functions.

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Our goals

- Analyze a general subspace-based framework.
- Inspiration: Model-based methods (Cartis and Roberts '23, Dzahini and Wild '22a).

Outline

Algorithm

Inputs: $\boldsymbol{x}_0 \in \mathbb{R}^n$, $\delta_0 > 0$.

Iteration k: Given $(\boldsymbol{x}_k, \delta_k)$,

- Choose $\boldsymbol{P}_k \in \mathbb{R}^{r \times n}$ **at random**.
- Choose $\mathcal{D}_k \subset \mathbb{R}^r$ having m vectors.
- If $\exists\ \boldsymbol{d}_k \in \mathcal{D}_k$ such that

$$f(\boldsymbol{x}_k + \delta_k \boldsymbol{P}_k^{\mathrm{T}} \boldsymbol{d}_k) < f(\boldsymbol{x}_k) - \delta_k^2 \|\boldsymbol{P}_k^{\mathrm{T}} \boldsymbol{d}_k\|^2,$$

  set $\boldsymbol{x}_{k+1} := \boldsymbol{x}_k + \delta_k \boldsymbol{P}_k^{\mathrm{T}} \boldsymbol{d}_k$, $\delta_{k+1} := 2\delta_k$.
- Otherwise, set $\boldsymbol{x}_{k+1} := \boldsymbol{x}_k$, $\delta_{k+1} := \delta_k / 2$.

Probabilistic properties

New polling sets

$$\left\{ \boldsymbol{P}_k^{\mathrm{T}} \boldsymbol{d} \;\middle|\; \boldsymbol{d} \in \mathcal{D}_k \right\} \subset \mathbb{R}^n.$$

- $\boldsymbol{P}_k \in \mathbb{R}^{r \times n}$: Maps onto r-dimensional subspace;
- $\mathcal{D}_k$: Direction set in $\mathbb{R}^r$.

What do we want?

- Preserve information while applying $\boldsymbol{P}_k / \boldsymbol{P}_k^{\mathrm{T}}$.
- Approximate $-\boldsymbol{P}_k \nabla f(\boldsymbol{x}_k)$ using $\mathcal{D}_k$.

Probabilistic properties for $\boldsymbol{P}_k$

$\boldsymbol{P}_k$ is $(\eta, \sigma, P_{\max})$-well aligned for $(f, \boldsymbol{x}_k)$ if

$$\left\{ \begin{array}{rcl} \|\boldsymbol{P}_k \nabla f(\boldsymbol{x}_k)\| & \geq & \eta \|\nabla f(\boldsymbol{x}_k)\|, \\ \sigma_{\min}(\boldsymbol{P}_k) & \geq & \sigma, \\ \sigma_{\max}(\boldsymbol{P}_k) & \leq & P_{\max}. \end{array} \right.$$

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Ex) $\boldsymbol{P}_k = \boldsymbol{I}_n \in \mathbb{R}^{n \times n}$ *is* $(1,1,1)$*-well aligned.*

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Probabilistic version

$\{\boldsymbol{P}_k\}$ is $(q, \eta, \sigma, P_{\max})$-well aligned if:

$$\begin{array}{rcl} \mathbb{P}\left(\boldsymbol{P}_0 \ (q, \eta, \sigma, P_{\max})\text{-well aligned }\right) & \geq & q \\ \forall k \geq 1, \quad \mathbb{P}\left((q, \eta, \sigma, P_{\max})\text{-well aligned } \mid \boldsymbol{P}_0, \mathcal{D}_0, \dots, \boldsymbol{P}_{k-1}, \mathcal{D}_{k-1}\right) & \geq & q, \end{array}$$

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Deterministic descent

The set $\mathcal{D}_k$ is $(\kappa, d_{\max})$-descent for $(f, \boldsymbol{x}_k)$ if

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Ex) $D_\oplus = \{\boldsymbol{e}_1, \dots, \boldsymbol{e}_n, -\boldsymbol{e}_1, \dots, -\boldsymbol{e}_n\}$ is $(\frac{1}{\sqrt{n}}, 1)$-descent.

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Probabilistic descent sets

$\{\mathcal{D}_k\}$ is $(p, \kappa, d_{\max})$-descent if:

$$\begin{aligned} \mathbb{P}\left(\mathcal{D}_0 \ (\kappa, d_{\max})\text{-descent} \ \middle| \ \boldsymbol{P}_0\right) &\geq p \\ \forall k \geq 1, \quad \mathbb{P}\left(\mathcal{D}_k \ (\kappa, d_{\max})\text{-descent} \ \middle| \ \boldsymbol{P}_0, \mathcal{D}_0, \dots, \boldsymbol{P}_{k-1}, \mathcal{D}_{k-1}, \boldsymbol{P}_k\right) &\geq p, \end{aligned}$$

Theorem (Roberts, R. '23)

Assume:

- $\{\mathcal{D}_k\}$ $(p, \kappa, d_{\max})$-descent, $|\mathcal{D}_k| = m$;
- $\{\boldsymbol{P}_k\}$ $(q, \eta, \sigma, P_{\max})$-well aligned, $pq > \frac{1}{2}$.

Let N_ϵ the number of function evaluations needed to have $\|\nabla f(\boldsymbol{x}_k)\| \leq \epsilon$.

$$\mathbb{P}\left(N_\epsilon \leq \mathcal{O}\left(\frac{m\phi\epsilon^{-2}}{2pq-1}\right)\right) \geq 1 - \exp\left(-\mathcal{O}\left(\frac{2pq-1}{pq}\phi\epsilon^{-2}\right)\right).$$

where $\phi = \eta^{-2}\sigma^{-2}P_{\max}^4 d_{\max}^8 \kappa^{-2}$.

Complexity analysis

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Does this bound depend on n?

Complexity and dimension dependencies

$$m\,\eta^{-2}\sigma^{-2}P_{\max}^4 d_{\max}^8\,\kappa^{-2}\epsilon^{-2}.$$

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A first simplification

- $\mathcal{D}_k = \{\boldsymbol{e}_1, \dots, \boldsymbol{e}_r, -\boldsymbol{e}_1, \dots, -\boldsymbol{e}_r\}$ in $\mathbb{R}^r$;
- $\kappa = \frac{1}{\sqrt{r}}$, $m = 2r$, $d_{\max} = 1$.

$\Rightarrow$ Bound becomes $2r^2\eta^{-2}\sigma^{-2}P_{\max}^4\epsilon^{-2}$.

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$$m\,\eta^{-2}\sigma^{-2}P_{\max}^{4}d_{\max}^{8}\,\kappa^{-2}\epsilon^{-2}.$$

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Using sketching techniques

$\mathbf{P}_k$	σ	$P_{\max}$
Identity	1	1
Gaussian	$\Theta(\sqrt{n/r})$	$\Theta(\sqrt{n/r})$
Hashing	$\Theta(\sqrt{n/r})$ (Dzahini & Wild '22b)	$\sqrt{n}$
Orthogonal	$\sqrt{n/r}$	$\sqrt{n/r}$.

$\Rightarrow$ Get a bound in $\mathcal{O}(n\epsilon^{-2})$ even when $r = \mathcal{O}(1)$ and $\eta = \mathcal{O}(1)$!

Benchmark:

- Medium-scale test set (90 CUTEst problems of dimension ≈ 100);
- Large-scale test set (28 CUTEst problems of dimension ≈ 1000).

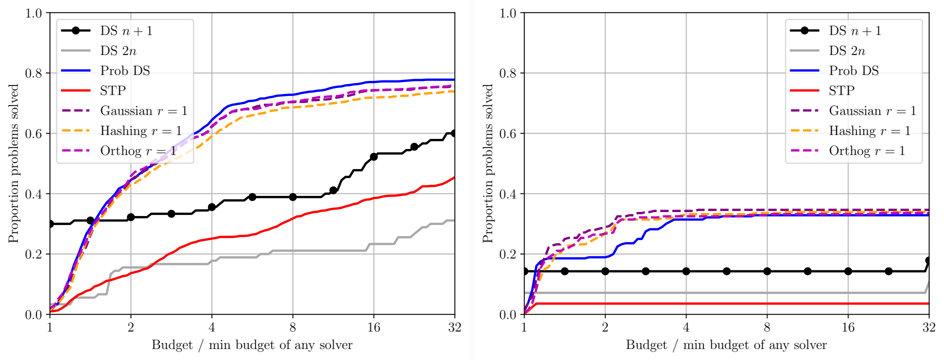
Budget: $200(n+1)$ evaluations.

Comparison:

- Deterministic DS with $\mathcal{D}_k = \mathcal{D}_\oplus$ or $\mathcal{D}_k = \{\boldsymbol{e}_1, \dots, \boldsymbol{e}_n, -\sum_{i=1}^n \boldsymbol{e}_i\}$;
- Probabilistic direct search with 2 uniform directions;
- Stochastic Three Point;
- Probabilistic direct search with Gaussian/Hashing/Orthogonal $\boldsymbol{P}_k$ matrices + 2 directions in the subspace.

Goal: Satisfy $f(\boldsymbol{x}_k) - f_{opt} \leq 0.1(f(\boldsymbol{x}_0) - f_{opt})$.

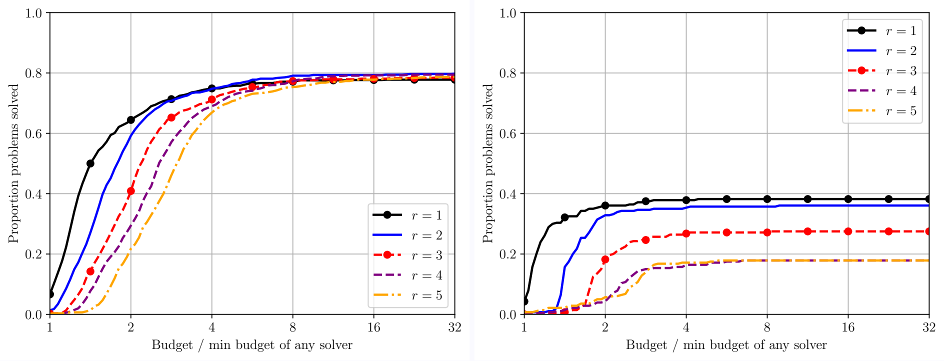
Comparison of all methods



Left: Medium scale; Right: Large scale.

- Can use less directions through sketching;
- But always a (hidden) dependency on n!

Gaussian matrices and the value of r



Left: Medium scale; Right: Large scale.

Numerically

- Sketches of dimension > 1 may improve things...
- ...but in general opposite (Gaussian) directions work best!

Summary of our findings

If you want to scale up...

- Can use less directions through sketching;
- But always a (hidden) dependency on n!

Numerically

- Sketches of dimension > 1 may improve things...
- ...but in general opposite Gaussian directions are quite good!

Outline

Warren: "But *why* does this work?"

Why one-dimensional subspaces?

- Best performance for 1-dimensional subspaces in general.
- Unclear why.

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Why one-dimensional subspaces?

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Our approach: Expected decrease guarantees

- Use Taylor approximation to focus on linear models

$$f(\boldsymbol{x}+\boldsymbol{d}) - f(\boldsymbol{x}) \le \nabla f(\boldsymbol{x})^{\mathrm{T}} \boldsymbol{d} + \frac{L}{2}\|\boldsymbol{d}\|^2.$$

- Analyze the **expected decrease guarantees** for those functions.

Theory

Key result (Hare, Roberts, R. '22)

Let $\boldsymbol{g} \in \mathbb{S}^{n-1}$, $\boldsymbol{P} \in \mathbb{R}^{r \times n}$ and $\mathcal{D} = \{\boldsymbol{e}_1, \dots, \boldsymbol{e}_r, -\boldsymbol{e}_1, \dots, -\boldsymbol{e}_r\}$.
Then, the expected decrease ratio

$$\frac{\mathbb{E}\left[\min_{\boldsymbol{d} \in \mathcal{D}} \boldsymbol{g}^{\mathrm{T}} \boldsymbol{P}^{\mathrm{T}} \boldsymbol{d}\right]}{2r}$$

is minimized at $r = 1$.

Side notes

- Proof based on the quantity

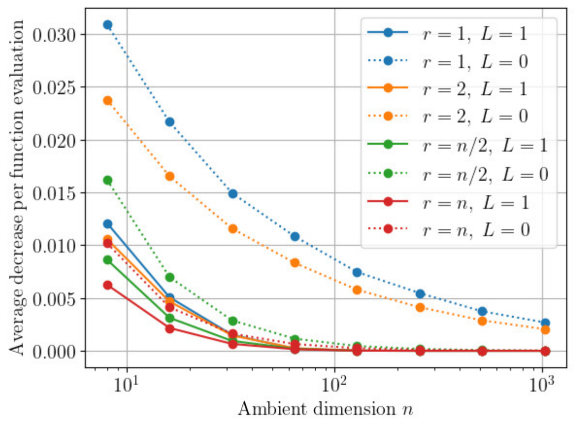
$$\mathbb{E}_{\boldsymbol{u} \sim \mathcal{U}(\mathbb{S}^{n-1})}\left[\max_{1 \leq r} |[\boldsymbol{u}]_i|\right].$$

- Exact values hard to find in the literature!
- When $\boldsymbol{g}$ is a gradient, guarantees that $r = 1$ gives the best "bang for your buck".

Numerical validation

Setup

- Monte-Carlo approximations of expected decrease.
- Quadratic functions with a random linear term $\boldsymbol{x} \mapsto \boldsymbol{g}^{\mathrm{T}}\boldsymbol{x} + \frac{L}{2}\|\boldsymbol{x}\|^2$.
- Normalization by the number of function evaluations.



Summary

Our findings

- A revised probabilistic analysis/subspace viewpoint;
- Good complexity ($\mathcal{O}(n)$).
- Motivation for using low-dimensional subspaces (works for other DFO methods!).

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Perspectives

- Stochastic function values.
- Correlated subspaces.

That's it!

References

- *Direct search based on probabilistic descent in reduced spaces*
  L. Roberts and C. W. Royer, SIAM J. Optim. 33(4):3057-3082, 2023.
- *Expected decrease for derivative-free algorithms using random subspaces*
  W. Hare, L. Roberts and C. W. Royer, Technical report arXiv:2308.04734v2, 2024.

The package

- `https://github.com/lindonroberts/directsearch`
- In Python, has all experiments.
- Recently used in the Meta **Nevergrad** software.

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Thank you for your attention!

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