

# The problem-dependent complexity of sequential optimization

Colloquium, Clermont-Ferrand

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March 20<sup>th</sup>, 2020

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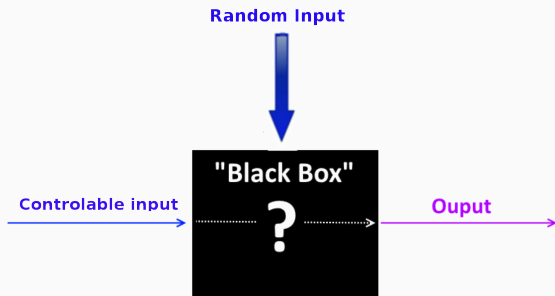
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# PAC Optimization

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# Random Experiment



Random black box

$$F : \mathcal{X} \times \Omega \rightarrow \mathbb{R}$$

where  $\mathcal{X}$  = space  $\mathcal{X}$  of controlled variables and  $\Omega$  = random space

**Target function**  $f : \mathcal{X} \rightarrow \mathbb{R}$   $f(x) = \mathbb{E}[F(x, \cdot)]$  or some other functional of  $F(x, \cdot)$

Typically (in the sequel):  $F(x, \omega) = f(x) + \epsilon(\omega)$  where  $\epsilon \sim \mathcal{N}(0, \sigma^2)$ .

# Black Box Optimization

**Black-box** interaction model:

- choose  $X_1 = \phi_1(U_1)$ , observe  $Y_1 = F(X_1, \omega_1)$
- choose  $X_2 = \phi_2(X_1, Y_1, U_2)$  observe  $Y_2 = F(X_2, \omega_2)$ ,
- etc...

**Target = optimize  $f$** :  $f^* = \max_{\mathcal{X}} f$  (or min, or find level set, etc.)

**Strategy**: sampling rule  $(\phi_t)_{t \geq 1}$ , stopping time  $\tau$

**PAC setting**: for a risk  $\delta$  and a tolerance  $\epsilon$ , return  $X_{\tau+1}$  such that

$$\mathbb{P}_f(f(X_{\tau+1}) < f^* - \epsilon) \leq \delta.$$

The set of correct answers is  $\mathcal{X}_\epsilon(f) = \{x \in \mathcal{X} : f(x) \geq f^* - \epsilon\}$ .

**Goal**: find a strategy minimizing  $\mathbb{E}_f[\tau]$  for all possible functions  $f$   
(no sub-optimal multiplicative constant!)

**Warm-up: 1.5 arms**

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## A Simplistic and yet Interesting Example

$\mathcal{X} = \{0, 1\}$ ,  $f = (0, \mu)$  ie.  $F(0, \cdot) = 0, F(1, \cdot) \sim \mathcal{N}(\mu, \sigma^2)$

Here,  $X_t = 1$  for  $t \leq \tau$  and  $Y_t \stackrel{iid}{\sim} \mathcal{N}(\mu, \sigma^2)$ .

Equivalent to testing the **overlapping** hypotheses:  $\mu \leq \epsilon$  vs  $\mu \geq -\epsilon$ .

### Theorem

For every  $(\epsilon, \delta)$ -PAC strategy,

$$\liminf_{\delta \rightarrow 0} \frac{\mathbb{E}_\mu[\tau_\delta]}{\log(1/\delta)} \geq \frac{2\sigma^2}{(|\mu| + \epsilon)^2}.$$

Besides, the choice

$$\tau_\delta = \inf \left\{ t \in \mathbb{N} : \frac{t(|\hat{\mu}_t| + \epsilon)^2}{2\sigma^2} > 3 \ln(\ln(t) + 1) + \mathcal{T}(\ln(1/\delta)) \right\},$$

where  $\mathcal{T}(x) \simeq x + 4 \ln(1 + x + \sqrt{2x})$  and  $X_{\tau+1} = \mathbb{1}\{\hat{\mu}_{\tau_\delta} > 0\}$  is such that  $\forall \mu \in \mathbb{R}$

$$\limsup_{\delta \rightarrow 0} \frac{\mathbb{E}_\mu[\tau_\delta]}{\ln(1/\delta)} \leq \frac{2\sigma^2}{(|\mu| + \epsilon)^2}.$$

## Lower Bounds: Information Inequalities

**Idea:** Cannot stop as long as an alternative hypothesis is likely to produce similar data.

**Alternative hypotheses:**  $\text{Alt}(f) = \{g : \mathcal{X} \rightarrow \mathbb{R} \text{ such that } \mathcal{X}_\epsilon(f) \not\subset \mathcal{X}_\epsilon(g)\}$

and not  $\mathcal{X}_\epsilon(f) \cap \mathcal{X}_\epsilon(g) = \emptyset$ : just "one of the correct answers for  $f$  is incorrect for  $g$ ".

Here,

- if  $\mu > \epsilon$ ,  $\text{Alt}(\mu) = (-\infty, -\epsilon)$
- if  $\mu < -\epsilon$ ,  $\text{Alt}(\mu) = (\epsilon, +\infty)$
- if  $-\epsilon \leq \mu \leq \epsilon$ ,  $\text{Alt}(\mu) = (-\infty, -\epsilon) \cup (\epsilon, +\infty)$



# Change-of-Measure Lemma

For a given strategy, likelihood of the observation under function  $f$ :  
 $\ell(Y_1, \dots, Y_t; f)$ .

Likelihood ratio  $L_t(f, g) := \log \frac{\ell(Y_1, \dots, Y_t; f)}{\ell(Y_1, \dots, Y_t; g)}$ .

## Lemma

Let  $f$  and  $g$  be two functions.

1. **Low-level form:** for all  $x \in \mathbb{R}$ ,  $n \in \mathbb{N}^*$ , for every event  $C \in \mathcal{F}_n$ ,

$$\mathbb{P}_g(C) \geq e^{-x} \left[ \mathbb{P}_f(C) - \mathbb{P}_f(L_n(f, g) \geq x) \right].$$

2. **High-level form:** for any stopping time  $\tau$  and any event  $C \in \mathcal{F}_\tau$ ,

$$\mathbb{E}_f[L_\tau(f, g)] = \text{KL} \left( \mathbb{P}_f^{X_1, \dots, X_\tau}, \mathbb{P}_g^{X_1, \dots, X_\tau} \right) \geq \text{kl}(\mathbb{P}_f(C), \mathbb{P}_g(C)),$$

where  $\text{kl}(x, y) = x \ln(x/y) + (1-x) \ln((1-x)/(1-y))$  is the binary relative entropy.

- Low-level form:

$$\begin{aligned}\mathbb{P}_g(C) &= \mathbb{E}_f \left[ \mathbf{1}_C \exp(-L_t(f, g)) \right] \geq \mathbb{E}_f \left[ \mathbf{1}_C \mathbf{1}_{\{L_t(f, g) < x\}} e^{-L_t(f, g)} \right] \\ &\geq e^{-x} \mathbb{P}_f \left( C \cap \{L_t(f, g) < x\} \right) \\ &\geq e^{-x} \left[ \mathbb{P}_f(C) - \mathbb{P}_f(L_n(f, g) \geq x) \right].\end{aligned}$$

- High-level form: Information Theory (data-processing inequality)

$$\begin{aligned}\mathbb{E}_\mu [L_\tau(f, g)] &= \text{KL} \left( \mathbb{P}_f^{X_1, \dots, X_\tau}, \mathbb{P}_g^{X_1, \dots, X_\tau} \right) \\ &\geq \text{KL} \left( \mathbb{P}_f^{1_C}, \mathbb{P}_g^{1_C} \right) = \text{kl}(\mathbb{P}_f(C), \mathbb{P}_g(C)).\end{aligned}$$

## 1.5 arm: Lower Bound for $|\mu| > \epsilon$

$\mathbb{E}_\mu[\tau] < \infty$  and Wald's lemma yield:

$$\mathbb{E}_\mu[L_\tau(\mu, \lambda)] = \mathbb{E}_\mu[\tau] \text{KL}\left(\mathcal{N}(\mu, \sigma^2), \mathcal{N}(\lambda, \sigma^2)\right) = \mathbb{E}_\mu[\tau] \frac{(\mu - \lambda)^2}{2\sigma^2}.$$

Hence, by the high-level form of the lemma:

$$\mathbb{E}_\mu[\tau] \frac{(\mu - \lambda)^2}{2\sigma^2} \geq \text{kl}(\mathbb{P}_\mu(C), \mathbb{P}_\lambda(C)).$$

For  $\mu < -\epsilon$ , choose  $\lambda = \epsilon$  and  $C = \{X_{\tau+1} = 1\}$

$\implies \mathbb{P}_\mu(C) \leq \delta$  and  $\mathbb{P}_\lambda(C) \geq 1 - \delta$  and

$$\mathbb{E}_\mu[\tau] \frac{(|\mu| + \epsilon)^2}{2\sigma^2} \geq \text{kl}(\delta, 1 - \delta) \approx \log \frac{1}{\delta}.$$

Similarly, for  $\mu > \epsilon$ , we use  $\lambda = -\epsilon$  and  $C = \{X_{\tau+1} = 0\}$  so as to obtain the same inequality.

$\implies$  non-asymptotic lower bound

## 1.5 arm: lower bound for $-\epsilon \leq \mu \leq \epsilon$

For a fixed  $\eta > 0$ . Introducing

$$n_\delta := \left\lceil \frac{2\sigma^2(1-\eta)}{(|\mu| + \epsilon)^2} \log \frac{1}{\delta} \right\rceil,$$

and the event  $C_\delta = \{\tau_\delta \leq n_\delta\}$ , we prove that

$$\mathbb{P}_\mu(\tau_\delta \leq n_\delta) = \mathbb{P}_\mu(C_\delta, X_{\tau+1} = 0) + \mathbb{P}_\mu(C_\delta, X_{\tau+1} = 1) \rightarrow 0 \text{ when } \delta \rightarrow 0.$$

Choosing  $\lambda = \epsilon$  yields that  $\mathbb{P}_\lambda(C_\delta, X_{\tau+1} = 0) \leq \mathbb{P}_\lambda(X_{\tau+1} = 0) \leq \delta$ . The event  $C_\delta \cap \{X_{\tau+1} = 0\}$  belongs to  $F_{n_\delta}$ . Hence, for all  $x \in \mathbb{R}$ ,

$$\delta \geq e^{-x} [\mathbb{P}_\mu(C_\delta, X_{\tau+1} = 0) - \mathbb{P}_\mu(L_{n_\delta}(\mu, \epsilon) \geq x)],$$

which can be rewritten as

$$\mathbb{P}_\mu(C_\delta, X_{\tau+1} = 0) \leq \delta e^x + \mathbb{P}_\mu(L_{n_\delta}(\mu, \epsilon) \geq x).$$

The choice  $x = (1 - \eta/2) \log(1/\delta)$  yields

$$\mathbb{P}_\mu(C_\delta, X_{\tau+1} = 0) \leq \delta^{\frac{\eta}{2}} + \mathbb{P}_\mu\left(\frac{L_{n_\delta}(\mu, \epsilon)}{n_\delta} \geq \frac{1 - \eta/2}{1 - \eta} \frac{(|\mu| + \epsilon)^2}{2\sigma^2}\right).$$

By the law of large numbers and the fact that  $n_\delta \rightarrow +\infty$  when  $\delta \rightarrow 0$ ,

$$\frac{L_{n_\delta}(\mu, \epsilon)}{n_\delta} \xrightarrow{\delta \rightarrow 0} \mathbb{E}_\mu \left[ \log \frac{\ell(X_1; \mu)}{\ell(X_1; \epsilon)} \right] = \text{KL}(\mathbb{P}_\mu^{X_1}, \mathbb{P}_\epsilon^{X_1}) = \frac{(\mu - \epsilon)^2}{2\sigma^2} < \frac{1 - \eta/2}{1 - \eta} \frac{(|\mu| + \epsilon)^2}{2\sigma^2}.$$

## Strategy: GLRT

**Idea:** cannot decide as long as incompatible hypotheses remain  $\delta$ -likely.

**Generalized Likelihood Ratio Test:**

$$\begin{aligned}\log \frac{\max_{\mu \in \mathcal{R}} \ell(X_1, \dots, X_t; \mu)}{\max_{\lambda \in \text{Alt}(\hat{t}_t)} \ell(X_1, \dots, X_t; \lambda)} &= \log \inf_{\lambda \in \text{Alt}(\hat{\mu}_t)} \frac{\ell(X_1, \dots, X_t; \hat{\mu}(t))}{\ell(X_1, \dots, X_t; \lambda)} \\ &= \inf_{\lambda \in \text{Alt}(\hat{\mu}_t)} \frac{t (\hat{\mu}_t - \lambda)^2}{2\sigma^2}\end{aligned}$$

where  $\hat{\mu}(t) = \frac{1}{s} \sum_{i=1}^t X_i$ . Here:

$$\begin{aligned}\tau_\delta &= \inf \left\{ t \in \mathbb{N} : \lambda \in \max_{\text{Alt}(\hat{\mu}_t)} \log \frac{\ell(X_1, \dots, X_t; \hat{\mu}(t))}{\ell(X_1, \dots, X_t; \lambda)} > \beta(t, \delta) \right\} \\ &= \inf \left\{ t \in \mathbb{N} : \frac{t(|\hat{\mu}_t| + \epsilon)^2}{2\sigma^2} > \beta(t, \delta) \right\}\end{aligned}$$

and

$$X_{\tau+1} = 1\{\hat{\mu}_{\tau_\delta} > 0\}$$

# Efficiency of the Sequential GLRT Procedure

Fix  $\mu \in \mathbb{R}$  and let  $\alpha \in [0, \epsilon)$ .

$$\begin{aligned}\mathbb{E}[\tau_\delta] &\leq \sum_{t=1}^{\infty} \mathbb{P} \left( t(|\hat{\mu}_t| + \epsilon)^2 \leq 2\sigma^2\beta(t, \delta) \right) \\ &\leq \sum_{t=1}^{\infty} \mathbb{P} (|\hat{\mu}_t - \mu| > \alpha) + \sum_{t=1}^{\infty} \mathbb{P} \left( t(|\hat{\mu}_t| + \epsilon)^2 \leq 2\sigma^2\beta(t, \delta), |\hat{\mu}_t - \mu| \leq \alpha \right) \\ &\leq \sum_{t=1}^{\infty} \mathbb{P} (|\hat{\mu}_t - \mu| > \alpha) + \sum_{t=1}^{\infty} \mathbb{P} \left( t(|\mu| - \alpha + \epsilon)^2 \leq 2\sigma^2\beta(t, \delta), |\hat{\mu}_t - \mu| \leq \alpha \right).\end{aligned}$$

The first term is upper bounded by a constant (independent of  $\delta$ ), while the second is upper bounded by

$$T_0(\delta) = \inf \left\{ T \in \mathbb{N}^* : \forall t \geq T, t(|\mu| - \alpha + \epsilon)^2 \leq 2\sigma^2\beta(t, \delta) \right\}.$$

For  $\beta(t, \delta) = 3 \ln(\ln(t) + 1) + \mathcal{T}(\ln(1/\delta))$ , since for every  $\alpha \geq 0$ ,  $\gamma \geq 1 + \alpha$  and  $t > 0$ ,

$$t \geq \gamma + 2\alpha \log(\gamma) \Rightarrow t \geq \gamma + \alpha \ln(t),$$

we have

$$T_0(\delta) = \frac{2\sigma^2}{(|\mu| - \alpha + \epsilon)^2} \log \frac{1}{\delta} + o_{\delta \rightarrow 0} \left( \log \frac{1}{\delta} \right).$$

Letting  $\alpha$  go to zero, one obtains, for all  $\mu \in \mathbb{R}$ ,

$$\limsup_{\delta \rightarrow 0} \frac{\mathbb{E}_\mu[\tau_\delta]}{\ln(1/\delta)} \leq \frac{2\sigma^2}{(|\mu| + \epsilon)^2}.$$

# **Discrete, Non-smooth Functions**

## **– The Vanilla Bandit Model**

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# Racing Strategy see [Kaufmann & Kalyanakrishnan '13]

$\mathcal{R} := \{1, \dots, K\}$  set of **remaining arms**.

$r := 0$  current round

**while**  $|\mathcal{R}| > 1$

- $r := r + 1$
- draw each  $x \in \mathcal{R}$ , compute  $\hat{f}_r(x)$ , the empirical mean of the  $r$  samples observed so far
- compute the **empirical best** and **empirical worst** arms:

$$b_r = \operatorname{argmax}_{x \in \mathcal{R}} \hat{f}_r(x) \quad w_r = \operatorname{argmin}_{x \in \mathcal{R}} \hat{f}_r(x)$$

as well as an ucb for  $w_r$  and an lcb for  $b_r$ .

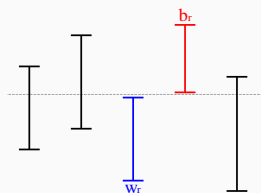
- Elimination step: if

$$\ell_{b_r}(r) > u_{w_r}(r),$$

then eliminate  $w_r$  :  $\mathcal{R} := \mathcal{R} \setminus \{w_r\}$

**end**

**Output**:  $\hat{x}$  the single element remaining in  $\mathcal{R}$ .





## The case $\epsilon = 0$

### Theorem [G. and Kaufmann, 2016]

For any  $\delta$ -correct algorithm,

$$\mathbb{E}_{\mu}[\tau] \geq T^*(\mu) \text{kl}(\delta, 1 - \delta),$$

where

$$\begin{aligned} T^*(\mu)^{-1} &= \sup_{w \in \Sigma_K} \inf_{g \in \text{Alt}(f)} \sum_{x \in \mathcal{X}} w(x) \text{kl}(f(x), g(x)) \\ &= \max_{w \in \Sigma_K} \min_{y \neq x^*(f)} \inf_{f(y) \leq \lambda \leq f^*} w(x^*(f)) \text{kl}(f^*, \lambda) + w(y) \text{kl}(f(y), \lambda). \end{aligned}$$

- A kind of **game**: you choose the proportions of draws  $w \in \Sigma_K$ , the opponent chooses the alternative confusing function.
- the **optimal proportions of arm draws** are

$$w^{*,f} = \operatorname{argmax}_{w \in \Sigma_K} \inf_{g \in \text{Alt}(f)} \sum_{x \in \mathcal{X}} w(x) \text{kl}(f(x), g(x)).$$

# Entropic Lower Bound (high-level form)

Assume that  $f$  and  $g$  have a different maximum  $x^*(f) \neq x^*(g)$ . Then

$$\begin{aligned} \sum_{x \in \mathcal{X}} \mathbb{E}_f [N_x(\tau)] \text{kl}(f(x), g(x)) &= \text{KL} \left( \mathbb{P}_f^{(X_1, \dots, X_\tau)}, \mathbb{P}_g^{(X_1, \dots, X_\tau)} \right) \\ &\geq \text{KL} \left( \mathbb{P}_f^{\mathbb{1}\{\hat{x}_\tau = x^*(f)\}}, \mathbb{P}_g^{\mathbb{1}\{\hat{x}_\tau = x^*(f)\}} \right) \\ &\geq \text{kl} \left( \mathbb{P}_f(\hat{x}_\tau = x^*(f)), \mathbb{P}_g(\hat{x}_\tau = x^*(f)) \right) \\ &\geq \text{kl}(1 - \delta, \delta) . \end{aligned}$$

## Entropic Lower Bound

[Kaufmann, Cappé, G.'15],[G., Ménard, Stoltz '16]

For every  $\delta$ -correct procedure, if  $x^*(f) \neq x^*(g)$  then

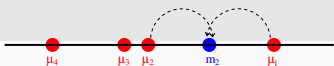
$$\sum_{x \in \mathcal{X}} \mathbb{E}_f [N_x(\tau)] \text{kl}(f(x), g(x)) \geq \text{kl}(1 - \delta, \delta) .$$

# Combining the Entropic Lower Bounds

## Entropic Lower Bound

If  $x^*(f) \neq x^*(g)$ , any  $\delta$ -correct algorithm satisfies

$$\sum_{x \in \mathcal{X}} \mathbb{E}_f [N_x(\tau)] \text{kl}(f(x), g(x)) \geq \text{kl}(\delta, 1 - \delta).$$



Let  $\text{Alt}(f) = \{g : x^*(g) \neq x^*(f)\}$ .

$$\inf_{g \in \text{Alt}(f)} \sum_{x \in \mathcal{X}} \mathbb{E}_{\mu} [N_x(\tau)] \text{kl}(f(x), g(x)) \geq \text{kl}(\delta, 1 - \delta)$$

$$\mathbb{E}_f[\tau] \times \inf_{g \in \text{Alt}(f)} \sum_{x \in \mathcal{X}} \frac{\mathbb{E}_f[N_x(\tau)]}{\mathbb{E}_f[\tau]} \text{kl}(f(x), g(x)) \geq \text{kl}(\delta, 1 - \delta)$$

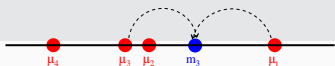
$$\mathbb{E}_f[\tau] \times \left( \sup_{w \in \Sigma_K} \inf_{g \in \text{Alt}(f)} \sum_{x \in \mathcal{X}} w(x) \text{kl}(f(x), g(x)) \right) \geq \text{kl}(\delta, 1 - \delta)$$

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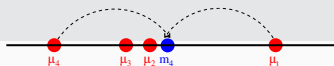
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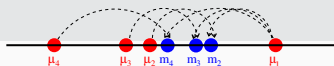
$$\mathbb{E}_f[\tau] \times \left( \sup_{w \in \Sigma_K} \inf_{g \in \text{Alt}(f)} \sum_{x \in \mathcal{X}} w(x) \text{kl}(f(x), g(x)) \right) \geq \text{kl}(\delta, 1 - \delta)$$

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$$\mathbb{E}_f[\tau] \times \inf_{g \in \text{Alt}(f)} \sum_{x \in \mathcal{X}} \frac{\mathbb{E}_f [N_x(\tau)]}{\mathbb{E}_f[\tau]} \text{kl}(f(x), g(x)) \geq \text{kl}(\delta, 1 - \delta)$$

$$\mathbb{E}_f[\tau] \times \left( \sup_{w \in \Sigma_{\mathcal{K}}} \inf_{g \in \text{Alt}(f)} \sum_{x \in \mathcal{X}} w(x) \text{kl}(f(x), g(x)) \right) \geq \text{kl}(\delta, 1 - \delta)$$

# Information Complexity of PAC Optimization

## Theorem

For any  $\epsilon$ -PAC family of converging strategies,

$$\liminf_{\delta \rightarrow 0} \frac{\mathbb{E}_f[\tau_\delta]}{\ln(1/\delta)} \geq T_\epsilon^*(f) = \sup_{w \in \Sigma_K} \max_{x \in \mathcal{X}_\epsilon(f)} \min_{y \neq x} \inf_{\substack{g \in \text{Alt}(f): \\ g(x) \leq g(y) - \epsilon}} w(x) \frac{(f(x) - g(x))^2}{2} + w(y) \frac{(f(y) - g(y))^2}{2},$$

where  $\Sigma_K = \{w \in [0, 1]^{\mathcal{X}} : \sum_x w(x) = 1\}$ .

- Two armed-case:  $T_\epsilon^*(f) = \frac{8\sigma^2}{(\text{osc}(f) + \epsilon)^2}$ .
- Approximation:

$$\sum_{y \neq x^*(f)}^K \frac{2\sigma^2}{(f^* + \epsilon - f(y))^2} \leq T_\epsilon^*(f) \leq 2 \times \sum_{y \neq x^*(f)}^K \frac{2\sigma^2}{(f^* + \epsilon - f(y))^2}.$$

- Computation: Denoting  $f^{x, \epsilon}$  the bandit instance such that  $f^{x, \epsilon}(y) = f(y)$  for all  $y \neq x$  and  $f^{x, \epsilon}(x) = f(x) + \epsilon$ ,

$$T_\epsilon^*(f) = \min_{x \in \mathcal{X}_\epsilon(f)} T_0(f^{x, \epsilon}) = T_0(f^{x^*(f), \epsilon}),$$

where  $x^*(f) \in \mathcal{X}^*(f)$  is an optimal arm  $\implies$  simple and efficient algorithm.

# GLRT stopping rule

$$\tau_\delta = \inf \left\{ t \in \mathbb{N} : \max_{x \in \mathcal{X}} \inf_{g \in \mathcal{R} \setminus \mathcal{R}_x} \sum_{y \in \mathcal{X}} N_y(t) d(\hat{f}_t(y), g(y)) > \beta(t, \delta) \right\},$$

$$X_{\tau+1} = \operatorname{argmax}_{x=1, \dots, M} \inf_{g \in \mathcal{R} \setminus \mathcal{R}_x} \sum_{y \in \mathcal{X}} N_y(\tau_\delta) d(\hat{f}_{\tau_\delta}(y), \lambda_j) = \operatorname{argmax}_{x \in \mathcal{X}} \hat{f}_\tau(x).$$

## Lemma

For any sampling rule, the parallel GLRT test  $(\tau_\delta, X_{\tau+1})$  using the threshold function

$$\beta(t, \delta) = 3K \ln(1 + \log t) + K\mathcal{T} \left( \frac{\ln(1/\delta)}{K} \right)$$

is  $\delta$ -correct: for all  $f \in \mathcal{R}$ ,  $\mathbb{P}_f \left( \tau_\delta < \infty, \hat{X}_{\tau+1} \notin \mathcal{X}^*(f) \right) \leq \delta$ .



# Tracking the Optimal Proportions

Sampling rule:

$$X_{t+1} \in \begin{cases} \operatorname{argmin}_{x \in U_t} N_x(t) & \text{if } U_t \neq \emptyset \quad (\text{forced exploration}), \text{ or otherwise} \\ \operatorname{argmax}_{x \in \mathcal{X}} t \times w_\epsilon^*, \hat{f}_t(x)(x) - N_x(t) & (\text{tracking the plug-in estimate}). \end{cases}$$

An instance  $(f, \epsilon)$  is **regular** if the set

$$\mathcal{W}_\epsilon^*(f) = \operatorname{argmax}_{w \in \Sigma_K} \max_{x \in \mathcal{X}_\epsilon} \min_{y \neq x} \inf_{\substack{(\lambda_x, \lambda_y): \\ \lambda_x \leq \lambda_y - \epsilon}} w(x) \frac{(f(x) - g(x))^2}{2} + w(y) \frac{(f(y) - g(y))^2}{2}$$

is of cardinality one. For a regular instance,  $\mathcal{W}_\epsilon^*(f) = \{w_\epsilon^*(f)\}$ .

## Lemma

Let  $(f, \epsilon)$  be a regular instance of almost optimal best arm identification. Then, under the  $\epsilon$ -Tracking sampling rule,

$$\mathbb{P}_f \left( \forall x \in \mathcal{X}, \lim_{t \rightarrow \infty} \frac{N_x(t)}{t} = w_\epsilon^*, f(x) \right) = 1.$$

# Optimality of the Track-and-Stop Algorithm

## Theorem

For every  $\delta \in (0, 1]$ , the  $\epsilon$ -TaS( $\delta$ ) algorithm is  $(\epsilon, \delta)$ -PAC. Moreover, for every *regular* instance  $(f, \epsilon)$ , if  $\tau_\delta$  denotes the stopping rule of  $\epsilon$ -TaS( $\delta$ ),

$$\limsup_{\delta \rightarrow 0} \frac{\mathbb{E}_f[\tau_\delta]}{\ln(1/\delta)} \leq T_\epsilon^*(f) .$$

# Experiments

Two regular instances

$$\begin{aligned} f_1 &= [0.2 \ 0.4 \ 0.5 \ 0.55 \ 0.7] & \epsilon_1 &= 0.1 \\ f_2 &= [0.4 \ 0.5 \ 0.6 \ 0.7 \ 0.75 \ 0.8] & \epsilon_2 &= 0.15, \end{aligned}$$

and one non-regular instance

$$f_3 = [0.2 \ 0.3 \ 0.45 \ 0.55 \ 0.6 \ 0.6] \quad \epsilon_3 = 0.1 .$$

	$T^*(f) \ln(1/\delta)$	$\epsilon$ -TaS	KL-LUCB	UGapE	KL-Racing
$f_1, \epsilon_1 = 0.1$	97	171 (104)	322 (137)	324 (143)	372 (159)
$f_2, \epsilon_2 = 0.15$	108	162 (83)	345 (135)	344 (141)	402 (146)
$f_3, \epsilon_3 = 0.1$	531	501 (261)	1236 (403)	1199 (414)	1348 (436)

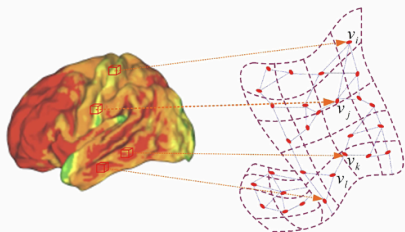
**Table 1:** Estimated values of  $\mathbb{E}_{\mu_i}[\tau_\delta]$  based on  $N = 1000$  repetitions for different instances and algorithms (standard deviation indicated in parenthesis).

# Graph Structure and Smooth Functions

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# Graph Smoothness

See [Spectral bandits for smooth graph functions, by M. Valko, R. Munos, B. Kveton, T. Kocák]



Src: A Spectral Graph Regression Model for Learning Brain Connectivity of Alzheimer's Disease ,by Hu, Cheng, Sepulcre and Li

Weighted graph structure with adjacency matrix  $\mathbf{W} = (w_{x,y})_{x,y \in \mathcal{X}}$ , and

$$S_G(f) \triangleq \sum_{x,y \in \mathcal{X}} w_{x,y} \frac{(f(x) - f(y))^2}{2} = f^T \mathcal{L} f = \|f\|_{\mathcal{L}}^2 \leq R$$

for some (known) smoothness parameter  $R$ , where  $\mathcal{L}$  is the **graph**

**Laplacian:**  $\mathcal{L}_{x,y} = -w_{x,y}$  for  $x \neq y$  and  $\mathcal{L}_{x,x} = \sum_{y \neq x} w_{x,y}$ .

$\implies$  The values of  $f$  at two points  $x, y \in \mathcal{X}$  are close if  $w_{x,y}$  is large.

# Complexity of Graph BAI

The set of considered signals is

$$\mathcal{M}_R = \{f \in \mathbb{R}^K : f^\top \mathcal{L} f \leq R\}$$

## Proposition

For any  $\delta$ -correct strategy and any  $R$ -smooth function  $f$ ,

$$\mathbb{E}_f[T_\delta] \geq T_R^*(f) \text{kl}(\delta, 1 - \delta)$$

where

$$T_R^*(f)^{-1} \triangleq \sup_{\omega \in \Delta_K} \inf_{g \in \mathcal{A}_R(f)} \sum_{x \in \mathcal{X}} \omega_x \frac{(f(x) - g(x))^2}{2} \quad (1)$$

for the set

$$\mathcal{A}_R(f) \triangleq \{g \in \mathcal{M}_R : \exists x \in \mathcal{X} \setminus \{\mathcal{X}_*(f)\}, g(x) \geq g(\mathcal{X}_*(\mu))\}$$

# Computing the Complexity

## Lemma

Let  $\mathcal{D} \subseteq \mathbb{R}^K$  be a compact set. Then function  $f : \Delta_K \rightarrow \mathbb{R}$  defined as  $f(\omega) = \inf_{d \in \mathcal{D}} \omega^\top d$  is a concave function and  $d^*(\omega) = \arg \min_{d \in \mathcal{D}} \omega^\top d$  is a supergradient of  $f$  at  $\omega$ .

## Lemma

Let  $h : \Delta_K \rightarrow \mathbb{R}$  be a function such that

$$h(w) = \inf_{g \in \text{Alt}_R(f)} \sum_{x \in \mathcal{X}} w(x) \frac{(f(x) - g(x))^2}{2}$$

Then function  $h$  is  $L$ -Lipschitz with respect to  $\|\cdot\|_1$  for any

$$L \geq \max_{x, y \in \mathcal{X}} \frac{(f(x) - f(y))^2}{2}.$$

# Mirror Ascent Algorithm

One can compute the best response  $g_w^*$  and therefore, the supergradient of concave function  $h(w) = \sum_{x \in \mathcal{X}} \omega_x k(f(x), g_w^*(x))$  at  $w$ .

## Proposition

For  $(\Delta_K, \|\cdot\|_1)$ ,  $w_1 = (\frac{1}{K}, \dots, \frac{1}{K})^\top$ ,  $Q = \sqrt{\log K}$ , for any  $L \geq \max_{x, u \in \mathcal{X}} \frac{(f(x) - f(y))^2}{2}$ , mirror ascent with generalized negative entropy as the mirror map

$$\Phi(w) = \sum_{x \in \mathcal{X}} w(x) \log(w(x)) - w(x)$$

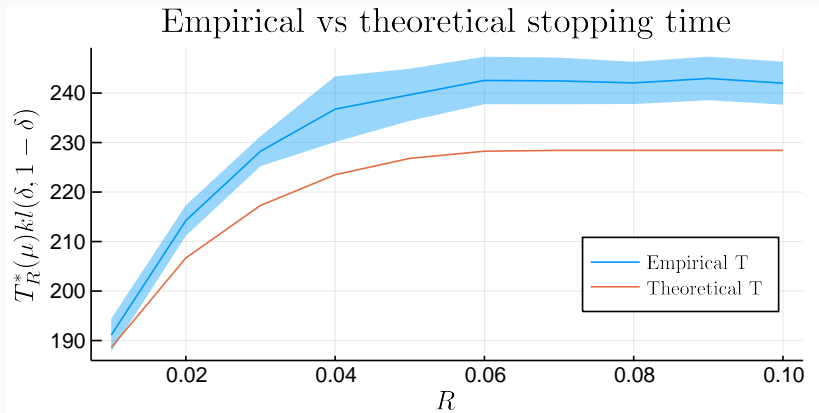
and  $\eta = \frac{1}{L} \sqrt{\frac{2 \log K}{t}}$  satisfies:

$$h(w^*) - h\left(\frac{1}{t} \sum_{s=1}^t w_s\right) \leq L \sqrt{\frac{2 \log K}{t}}.$$



- 1: **Input and initialization:**
- 2:  $\mathcal{L}$  : graph Laplacian
- 3:  $\delta$  : confidence parameter
- 4:  $R$  : upper bound on the smoothness of  $f$
- 5: Play each  $x \in \mathcal{X}$  once and observe rewards  $F(x, \omega)$
- 6:  $\hat{f}_t$  = empirical estimate of  $f$
- 7: **while** Stopping Rule not satisfied **do**
- 8:   Compute  $\omega^*(\hat{f}_t)$  by mirror ascent
- 9:   Choose  $X_t$  according to Tracking Sampling Rule
- 10:   Obtain reward  $F(X_t, \omega_t)$
- 11:   Update  $\hat{f}_t$  accordingly
- 12: **end while**
- 13:   Output arm  $\hat{x} = \operatorname{argmax}_{x \in \mathcal{X}} \hat{f}(x)$

# Experiment



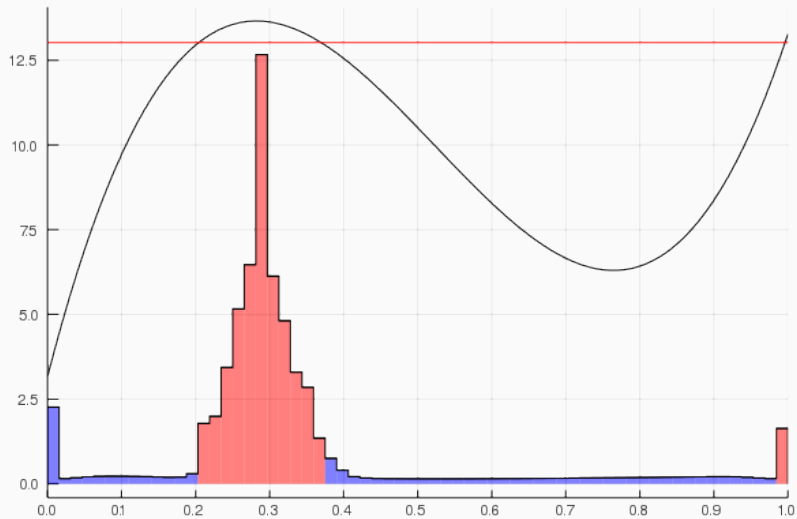
# Optimizing a Continuous Function

- Need a way to encode the *regularity* of the function.
- Discretization: graph = grid
- Idea 1: Lipschitz  $\implies$  neighbors means differ by at most  $L$
- Idea 2: Graph Laplacian regularity

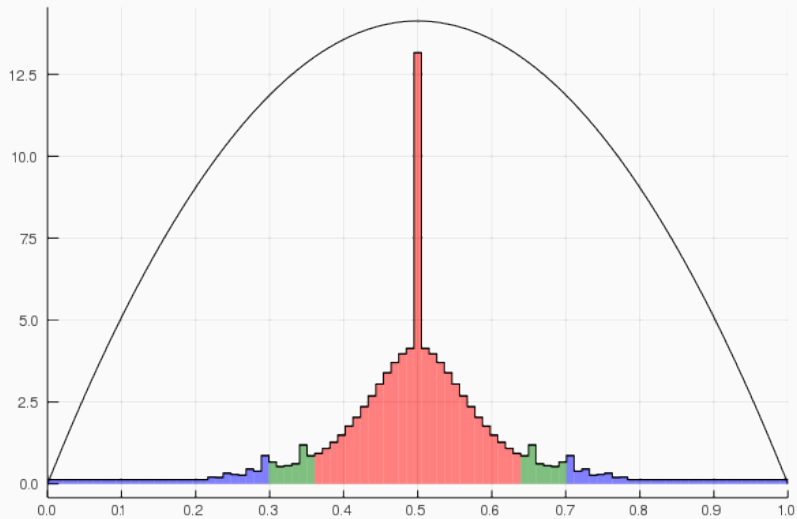
$$\implies \int_{R^d} \|\nabla f(x)\|^2 dx \leq C .$$

- Question: what happens when the grid refines? Is there a *limit*?
  - Limiting Complexity of  $\epsilon, \delta$ -PAC optimization?
  - Limiting density of optimal arm draws?
  - How do known methods compare?

# Example



## Example (large $\epsilon$ )



## Example (small $\epsilon$ )

