Experimental design in nonlinear models: small-sample properties

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1 Introduction

Regression model

$$\underbrace{y_i = y(x_i)}_{\text{observation at } x_i} = \overbrace{\eta(x_i, \bar{\theta})}^{\text{model response at } x_i} + \underbrace{\varepsilon_i}_{\text{error}}$$

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$\mathbf{X}_n = (x_1, \ldots, x_n)$ the design

$\mathbf{y} = (y_1, \ldots, y_n)^\top$ the vector of observations

$\boldsymbol{\eta}(\theta) = (\eta(x_1, \theta), \ldots, \eta(x_n, \theta))^\top$ the vector of model responses

$\boldsymbol{\varepsilon} = (\varepsilon_1, \ldots, \varepsilon_n)^\top$ the errors ($\rightarrow \mathsf{E}\{\boldsymbol{\varepsilon}\} = \mathbf{0}$ and $\mathrm{Var}(\boldsymbol{\varepsilon}) = \sigma^2\, \mathbf{I}_n$)

$\bar{\theta}$ = true value of the model parameters $\theta \in \mathbb{R}^p$

Least Squares (LS) estimator: $\boxed{\hat{\theta}^n = \arg\min_\theta \|\mathbf{y} - \boldsymbol{\eta}(\theta)\|^2}$

Information matrix (at θ^0, normalised — per observation)

$$\mathbf{M}(\mathbf{X}_n,\theta^0) = \frac{1}{n}\sum_{i=1}^{n} \frac{\partial\eta(x_i,\theta)}{\partial\theta}\Big|_{\theta^0} \frac{\partial\eta(x_i,\theta)}{\partial\theta^\top}\Big|_{\theta^0} = \frac{1}{n}\frac{\partial\boldsymbol{\eta}^\top(\theta)}{\partial\theta}\Big|_{\theta^0} \frac{\partial\boldsymbol{\eta}(\theta)}{\partial\theta^\top}\Big|_{\theta^0}$$

(a $p \times p$ matrix, with $p = \dim(\theta)$)

A. Linear regression

$\eta(x,\theta) = \mathbf{f}^\top(x)\theta \rightarrow \frac{\partial\eta^\top(\theta)}{\partial\theta} = \mathbf{F}^\top = (\mathbf{f}(x_1),\ldots,\mathbf{f}(x_n))$ and

$$\boxed{\hat{\theta}^n = (\mathbf{F}^\top\mathbf{F})^{-1}\mathbf{F}^\top\mathbf{y}}$$

normalised information matrix: $\mathbf{M}_n = \mathbf{M}(\mathbf{X}_n) = \frac{1}{n}\mathbf{F}^\top\mathbf{F}$

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$\Rightarrow \mathsf{E}\{\hat{\theta}^n\} = \bar{\theta}$

$\Rightarrow \mathrm{Var}(\hat{\theta}^n) = \mathsf{E}\{(\hat{\theta}^n - \bar{\theta})(\hat{\theta}^n - \bar{\theta})^\top\} = \frac{\sigma^2}{n}\mathbf{M}_n^{-1}$

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or maximise a function $\Phi(\mathbf{M}_n)$ (information function (Pukelsheim, 1993))

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Normal errors $\epsilon \sim \mathcal{N}(\mathbf{0}, \sigma^2\,\mathbf{I}_n)$ ➠ $\boxed{\hat{\theta}^n \sim \mathcal{N}(\bar{\theta}, \frac{\sigma^2}{n}\mathbf{M}^{-1}(\mathbf{X}_n))}$

→ no particular problem with *small data*

B. Nonlinear regression

$\eta(x,\theta)$ nonlinear in θ

Under «standard» assumptions ($\theta \in \Theta$ compact, $\eta(x,\theta)$ continuous in θ for any $x\ldots$), for a suitable sequence (x_i),

$\boxed{\hat{\theta}^n \stackrel{\text{a.s.}}{\to} \bar{\theta} \text{ as } n \to \infty}$ (strong consistency) [but $\mathsf{E}\{\hat{\theta}^n\} \neq \bar{\theta}$ ($\hat{\theta}^n$ is biased)]

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normalised information matrix at θ: $\mathbf{M}_n(\theta) = \mathbf{M}(\mathbf{X}_n, \theta) = \frac{1}{n} \sum_{i=1}^{n} \frac{\partial \eta(x_i, \theta)}{\partial \theta} \frac{\partial \eta(x_i, \theta)}{\partial \theta^\top}$

Under «standard» regularity assumptions ($\eta(x, \theta)$ twice continuously differentiable w.r.t. θ for any $x \ldots$), for a suitable sequence (x_i),

$$\boxed{\sqrt{n}(\hat{\theta}^n - \bar{\theta}) \stackrel{\text{d}}{\to} \mathcal{N}(\mathbf{0}, \sigma^2\, \mathbf{M}^{-1}(\bar{\theta})) \text{ as } n \to \infty} \text{ (asymptotic normality)}$$

with $\mathbf{M}(\theta) = \lim_{n \to \infty} \mathbf{M}_n(\theta)$

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→ choose the x_i to minimise a scalar function of $\mathbf{M}_n^{-1}(\theta^0)$,
or maximise a function $\Phi(\mathbf{M}_n(\theta^0))$, for a prior guess θ^0 (local design)

= **classical approach for DoE in nonlinear models**
(based on asymptotic normality)

- 1) DoE for linear models (local design for nonlinear models, for a given θ^0)
  - Which information function Φ?
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- 3,4,5,6) Small-sample issues
- 7) nonlocal DoE for nonlinear models (based on asymptotic normality)

2 DoE for linear models

Design criterion Φ

- A-optimality: minimise $\mathrm{trace}[\mathbf{M}^{-1}] \Leftrightarrow$ maximise $\Phi(\mathbf{M}) = 1/\mathrm{trace}[\mathbf{M}^{-1}]$
  $\Leftrightarrow$ minimise sum of lengthes^2 of axes of (asymptotic) confidence ellipsoids

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- *E*-optimality: maximise $\Phi(\mathbf{M}) = \lambda_{\min}(\mathbf{M})$
  $\Leftrightarrow$ minimise longest axis of (asymptotic) confidence ellipsoids
- *D*-optimality: maximise $\Phi(\mathbf{M}) = \det^{1/p}(\mathbf{M})$ $[p = \dim(\theta)]$
  $\Leftrightarrow$ minimise volume of (asymptotic) confidence ellipsoids
  (proportional to $1/\sqrt{\det(\mathbf{M})}$)
  Very much used:
    - a *D*-optimum design is invariant by reparameterisation

$$\det \mathbf{M}'(\beta(\theta)) = \det \mathbf{M}(\theta) \det^{-2}\left(\frac{\partial \beta}{\partial \theta^\top}\right)$$

    - often leads to repeat the same experimental conditions (replications)

Construction of an optimal design

A/ Exact design

n observations at $\mathbf{X}_n = (x_1, \ldots, x_n)$ in a regression model (for simplicity)
Each design point x_i can be anything, e.g. a point in a subset $\mathscr{X}$ of $\mathbb{R}^d$

Maximise $\Phi(\mathbf{M}_n)$ w.r.t. $\mathbf{X}_n$ with $\mathbf{M}_n = \mathbf{M}(\mathbf{X}_n) = \frac{1}{n}\sum_{i=1}^{n} \mathbf{f}(x_i)\mathbf{f}^\top(x_i)$

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  [but there exist constraints ($x_i \in \mathscr{X}$ for all i), local optimas. . .]

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- Otherwise → take the particular form of the problem into account

Exchange methods: (Fedorov, 1972; Mitchell, 1974)
At iteration k, exchange **one** *support point* x_j by a better one x^* in $\mathscr{X}$ in the sense of $\Phi(\cdot)$

$$\mathbf{X}_n^k = \left(x_1, \ldots, \boxed{\begin{matrix} x_j \\ \updownarrow \\ x^* \end{matrix}}, \ldots, x_n\right)$$

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- Branch and bound (Welch, 1982), rounding an optimal design measure (Pukelsheim and Reider, 1992)

B/ Design measures: approximate design theory

(Chernoff, 1953; Kiefer and Wolfowitz, 1960; Fedorov, 1972; Silvey, 1980; Pázman, 1986; Pukelsheim, 1993; Fedorov and Leonov, 2014)

$$\boxed{\mathbf{M}(\mathbf{X}_n) = \frac{1}{n}\sum_{i=1}^{n} \mathbf{f}(x_i)\mathbf{f}^\top(x_i)}$$

[with $\mathbf{M}(\mathbf{X}_n) = \mathbf{M}(\mathbf{X}_n, \theta^0)$ and $\mathbf{f}(x_i) = \frac{\partial \eta(x_i,\theta)}{\partial \theta}\Big|_{\theta^0}$ in a nonlinear model]
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Repeat r_i observations at the same $x_i \in \mathscr{X}$ (r_i replications):
→ only $m \leq n$ different x_i

$$\boxed{\mathbf{M}(\mathbf{X}_n) = \sum_{i=1}^{m} \frac{r_i}{n}\, \mathbf{f}(x_i)\mathbf{f}^\top(x_i)}$$

$$\begin{aligned} \frac{r_i}{n} &= \text{proportion of observations collected at } x_i \\ &= \text{«percentage of experimental effort» at } x_i \\ &= \text{weight } w_i \text{ of support point } x_i \end{aligned}$$

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➔ design $\mathbf{X}_n \Leftrightarrow \left\{ \begin{array}{ccc} x_1 & \cdots & x_m \\ w_1 & \cdots & w_m \end{array} \right\}$ with $\sum_{i=1}^m w_i = 1$

➔ normalised discrete distribution on $\mathscr{X}$, with $\boxed{\text{constraints } r_i/n = w_i}$

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More general expression: ξ = any probability measure on $\mathscr{X}$ $\left(\int_{\mathscr{X}} \xi(\mathrm{d}x) = 1\right)$

$$\boxed{\mathbf{M}(\xi) = \int_{\mathscr{X}} \mathbf{f}(x)\mathbf{f}^\top(x)\, \xi(\mathrm{d}x)}$$

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$\mathbf{M}(\xi) \in$ convex closure of the set of rank 1 matrices $\mathbf{f}(x)\mathbf{f}^\top(x)$
$\mathbf{M}(\xi)$ is symmetric $p \times p$, belongs to a $\frac{p(p+1)}{2}$-dimensional space
Caratheodory Theorem ➞ for any ξ, there exists a discrete probability measure ξ_d
with $\frac{p(p+1)}{2} + 1$ support points at most, such that $\mathbf{M}(\xi_d) = \mathbf{M}(\xi)$
(true in particular for the optimum design)

Maximise $\Phi[\mathbf{M}(\xi)]$, $\Phi(\cdot)$ concave (e.g., A, E, D-optimality) and $\mathbf{M}(\xi)$ linear in ξ

→ convex programming

Usually, $\mathscr{X}$ is first discretised

→ optimise a vector of weights
(possibly high dimensional, but the solution is sparse)

Typical algorithm when Φ is differentiable (A, D-optimality):
Frank-Wolfe conditional gradient (called vertex-direction algorithm in DoE), with predefined (Wynn, 1970) or optimal (Fedorov, 1972) step-size

[but there exist more efficient methods]

More difficult if Φ not differentiable (E-optimality), but feasible

Application to models with complete product-type interactions

Single factor models: $\eta_k(x,\theta^{(k)}) \triangleq [\mathbf{f}^{(k)}(x)]^\top \theta^{(k)}$

global model for d factors $\mathbf{x} = (\{\mathbf{x}\}_1, \{\mathbf{x}\}_2, \ldots, \{\mathbf{x}\}_d)^\top$:

$$\eta(\mathbf{x},\gamma) = [\mathbf{f}_1(\{\mathbf{x}\}_1) \otimes \cdots \otimes \mathbf{f}_d(\{\mathbf{x}\}_d)]^\top \gamma$$

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In particular, if $\eta_k =$ polynomial of degree d_k $(\dim(\theta^{(k)}) = p_k = 1 + d_k)$,

$\eta =$ polynomial with total degree $\sum_{k=1}^d d_k$ $(\dim(\gamma) = \prod_{k=1}^d p_k)$

Example:

$$\begin{aligned} \mathbf{f}^\top(\mathbf{x})\gamma &= (\theta_0^{(1)} + \theta_1^{(1)}\{\mathbf{x}\}_1 + \theta_2^{(1)}\{\mathbf{x}\}_1^2) \times (\theta_0^{(2)} + \theta_1^{(2)}\{\mathbf{x}\}_2 + \theta_2^{(2)}\{\mathbf{x}\}_2^2) \\ &= \gamma_0 + \gamma_1\{\mathbf{x}\}_1 + \gamma_2\{\mathbf{x}\}_2 + \gamma_{12}\{\mathbf{x}\}_1\{\mathbf{x}\}_2 + \gamma_{11}\{\mathbf{x}\}_1{}^2 + \gamma_{22}\{\mathbf{x}\}_2{}^2 \\ &\quad +\gamma_{112}\{\mathbf{x}\}_1{}^2\{\mathbf{x}\}_2 + \gamma_{122}\{\mathbf{x}\}_1\{\mathbf{x}\}_2{}^2 + \gamma_{1122}\{\mathbf{x}\}_1{}^2\{\mathbf{x}\}_2{}^2 \end{aligned}$$

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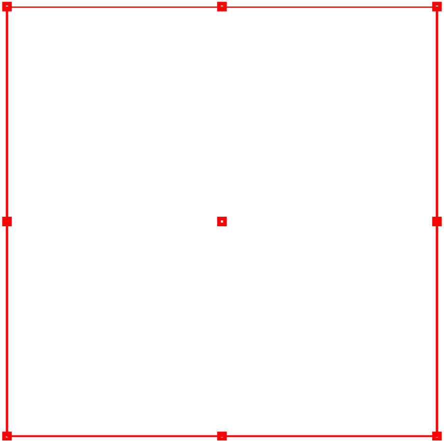
D, *A* and *E*-optimal design measure = tensor product of the d optimal design measures (Schwabe, 1996)

(true for any complete product-type interaction model — not only for polynomials)

Polynomial with degree k: D-optimal design supported on $k+1$ points
(on $[-1,1]$: roots of $(1-t^2)P_k'(t)$, with $P_k(t) \triangleq k$-th de Legendre polynomial),
all with the same weight $1/(k+1)$

dimension 2, $d_1 = d_2 = 2$
ξ^* has 9 support points, weights $=1/9$



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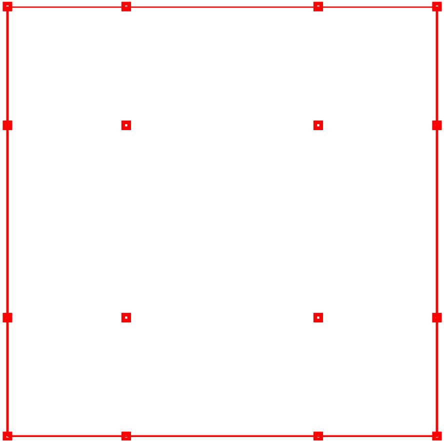
dimension 2, $d_1 = d_2 = 3$
ξ^* has 16 support points, weights $=1/16$



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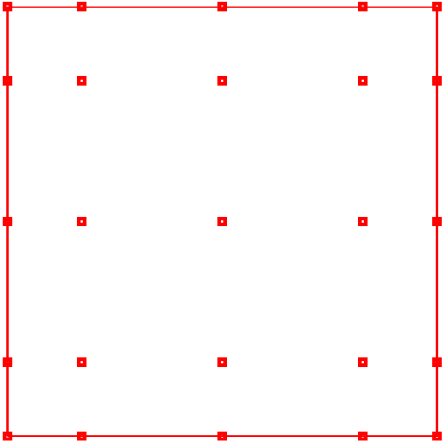
dimension 2, $d_1 = d_2 = 4$
ξ^* has 25 support points, weights $=1/25$



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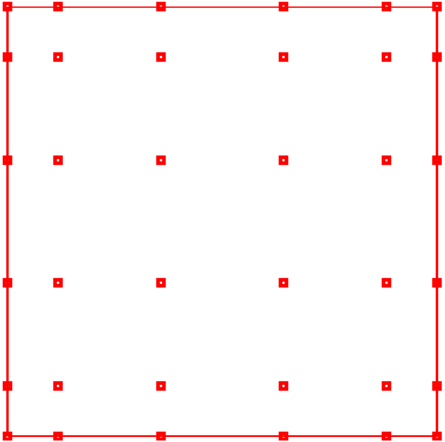
all with the same weight $1/(k+1)$

dimension 2, $d_1 = d_2 = 5$
ξ^* has 36 support points, weights $=1/36$



Application to models with intercept, no interaction

Single factor models: $\eta_k(x,\theta^{(k)}) \triangleq \theta_0^{(k)} + \sum_{i=1}^{d_k} \theta_i^{(k)} f_i^{(k)}(x)$

global model for d factors: $\eta(\mathbf{x},\gamma) = \theta_0 + \sum_{k=1}^{d} \sum_{i=1}^{d_k} \theta_i^{(k)} f_i^{(k)}(\{\mathbf{x}\}_k)$

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In particular, if η_k = polynomial of degree d_k $(\dim(\theta^{(k)}) = p_k = 1 + d_k)$,

η = polynomial with total degree $\max_k^d d_k$ $(\dim(\gamma) = 1 + \sum_{k=1}^{d} d_k)$

Example:

$$\begin{aligned} \mathbf{f}^\top(\mathbf{x})\gamma &= (\theta_0^{(1)} + \theta_1^{(1)}\{\mathbf{x}\}_1 + \theta_2^{(1)}\{\mathbf{x}\}_1^2) + (\theta_0^{(2)} + \theta_1^{(2)}\{\mathbf{x}\}_2 + \theta_2^{(2)}\{\mathbf{x}\}_2^2) \\ &= \gamma_0 + \gamma_1\{\mathbf{x}\}_1 + \gamma_2\{\mathbf{x}\}_2 + \gamma_{11}\{\mathbf{x}\}_1{}^2 + \gamma_{22}\{\mathbf{x}\}_2{}^2 \end{aligned}$$

D-optimal design measure = tensor product of d D-optimal measures (Schwabe, 1996)

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\end{aligned}
$$

D-optimal design measure = tensor product of d D-optimal measures (Schwabe, 1996)

Hardly manageable in high dimension

(d polynomials of degree k ➠ $(k+1)^d$ support points),

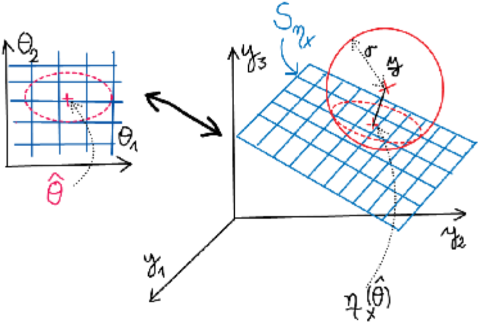
but maybe a useful message for Gaussian Process models and kriging:

➔ put more points along the boundaries than deeply inside

(Dette and Pepelyshev, 2010)

3 Linear and nonlinear models

Linear regression: easy



The expectation surface $\mathbb{S}_\eta = \{\boldsymbol{\eta}(\theta) = (\eta(x_1, \theta), \ldots, \eta(x_n, \theta))^\top : \theta \in \mathbb{R}^p\}$ is flat and linearly parameterised

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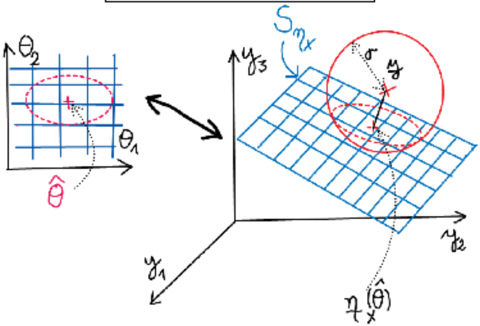

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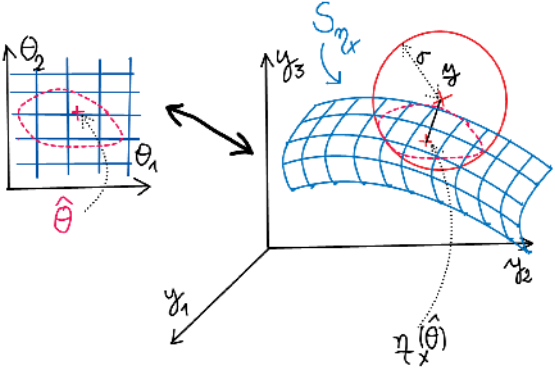
$\mathbf{M}(\mathbf{X}_n,\theta)$ does not depend on θ

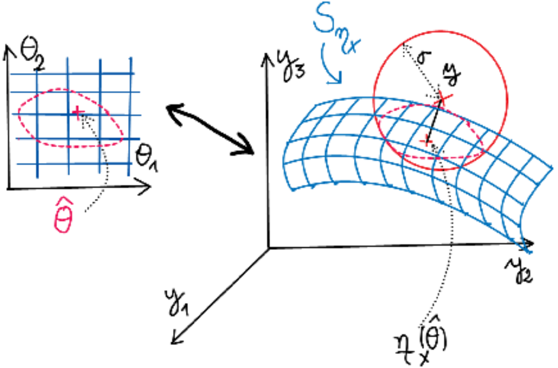
Normal errors $\epsilon \sim \mathcal{N}(\mathbf{0},\sigma^2\,\mathbf{I}_n)$ ➡ $\hat{\theta}^n \sim \mathcal{N}(\bar{\theta},\frac{\sigma^2}{n}\mathbf{M}^{-1}(\mathbf{X}_n))$

Nonlinear regression: maybe a bit tricky. . .



$\mathbb{S}_\eta$ is curved (intrinsic curvature) and nonlinearly parameterised (parametric curvature) (Bates and Watts, 1980)

Nonlinear regression: maybe a bit tricky...



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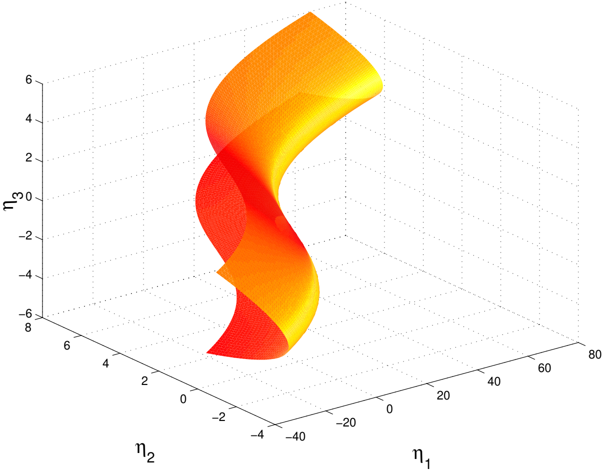
Normal errors $\epsilon \sim \mathcal{N}(\mathbf{0}, \sigma^2 \mathbf{I}_n)$ ➡ $\hat{\theta}^n \sim$ **?**

Ex: $\eta(\mathbf{x},\theta) = \theta_1\{\mathbf{x}\}_1 + \theta_1^3(1-\{\mathbf{x}\}_1) + \theta_2\{\mathbf{x}\}_2 + \theta_2^2(1-\{\mathbf{x}\}_2)$
$\mathbf{X} = (\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)$, $\mathbf{x}_1 = (0\ 1)$, $\mathbf{x}_2 = (1\ 0)$, $\mathbf{x}_3 = (1\ 1)$, $\theta \in [-3,4] \times [-2,2]$



Two major difficulties with nonlinear models:

❶ Asymptotically ($n \to \infty$) — or if σ^2 small enough — all seems fine:
use linear approximation

But the distribution of $\hat{\theta}^n$ may be far from normal for small n (or for σ^2 large)
➠ small-sample properties

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❷ Everything is local (depends on θ): if we linearise, where do we linearise?
(choice of a nominal value θ^0)
➠ nonlocal optimum design

4 Small-sample properties

Asymptotically $(n \to \infty)$ ➨ $\boxed{\sqrt{n}(\hat{\theta}^n - \bar{\theta}) \sim \mathscr{N}(\mathbf{0}, \sigma^2 \mathbf{M}^{-1}(\mathbf{X}_n, \bar{\theta}))}$

but what is the small sample precision?

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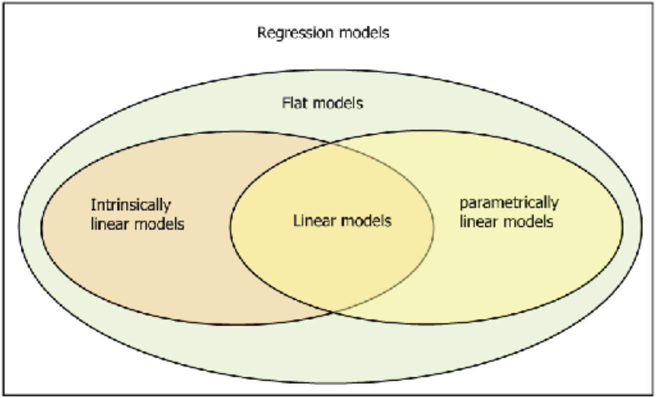
A classification of regression models (Pázman, 1993)



➔ Consider projection on the expectation surface $\mathbb{S}_\eta$:

➤ $\mathbf{P}_{\theta^0}$ = orthogonal projector onto the tangent space to $\mathbb{S}_\eta$ at $\boldsymbol{\eta}(\theta^0)$:

$$\mathbf{P}_{\theta^0} = \frac{1}{n}\frac{\partial\boldsymbol{\eta}(\theta)}{\partial\theta^\top}\Big|_{\theta^0}\mathbf{M}^{-1}(\mathbf{X}_n,\theta^0)\frac{\partial\boldsymbol{\eta}^\top(\theta)}{\partial\theta}\Big|_{\theta^0}$$

(an $n\times n$ matrix, depends on $\mathbf{X}_n$)
Bates and Watts (1980) intrinsic and parametric-effect measures of nonlinearity:

$$C_{int}(\mathbf{X}_n,\theta;\mathbf{u}) = \frac{\|[\mathbf{I}_n-\mathbf{P}_\theta]\sum_{i,j=1}^p u_i\mathbf{H}_{\boldsymbol{:}ij}(\theta)u_j\|}{n\,\mathbf{u}^\top\mathbf{M}(\mathbf{X}_n,\theta)\mathbf{u}}$$

$$C_{par}(\mathbf{X}_n,\theta;\mathbf{u}) = \frac{\|\mathbf{P}_\theta\sum_{i,j=1}^p u_i\mathbf{H}_{\boldsymbol{:}ij}(\theta)u_j\|}{n\,\mathbf{u}^\top\mathbf{M}(\mathbf{X}_n,\theta)\mathbf{u}}$$

with $\mathbf{u}\in\mathbb{R}^p$ and $\mathbf{H}_{\boldsymbol{:}ij}(\theta) = \frac{\partial^2\boldsymbol{\eta}(\theta)}{\partial\theta_i\partial\theta_j}$

Intrinsic curvature: $C_{int}(\mathbf{X}_n,\theta) = \sup_{\mathbf{u}\in\mathbb{R}^p\setminus\{\mathbf{0}\}} C_{int}(\mathbf{X}_n,\theta;\mathbf{u})$
Parametric curvature: $C_{par}(\mathbf{X}_n,\theta) = \sup_{\mathbf{u}\in\mathbb{R}^p\setminus\{\mathbf{0}\}} C_{par}(\mathbf{X}_n,\theta;\mathbf{u})$

Intrinsically linear models

- The expectation surface $\mathbb{S}_\eta = \{\boldsymbol{\eta}(\theta) : \theta \in \mathbb{R}^p\}$ is flat (plane) — intrinsic curvature $\equiv 0$
- There exists a reparameterisation (continuously differentiable) that makes the model linear
- $\mathbf{P}_\theta \mathbf{H}_{\cdot ij}(\theta) = \mathbf{H}_{\cdot ij}(\theta)$, where $\mathbf{H}_{\cdot ij}(\theta) = \frac{\partial^2 \boldsymbol{\eta}(\theta)}{\partial\theta_i \partial\theta_j}$

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Observing at p different x_i only (replications) makes the model intrinsically linear
$[p = \dim(\theta)]$

Parametrically linear models

- $\mathbf{M}(\mathbf{X}_n, \theta) = \text{constant}$
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Linear models

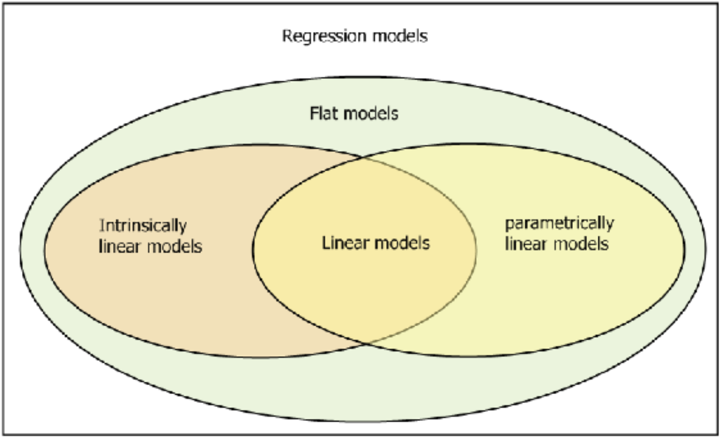
- $\eta(x, \theta) = \mathbf{f}^\top(x)\theta + c(x)$
- the model is intrinsically and parametrically linear

Flat models

- A reparameterisation exists that makes the information matrix constant
- Riemannian curvature tensor $R_{hijk}(\theta) = T_{hjik}(\theta) - T_{hkij}(\theta) \equiv 0$
  with $T_{hjik}(\theta) = [\mathbf{H}_{hj}^{\cdot\cdot}(\theta)]^\top [\mathbf{I}_n - \mathbf{P}_\theta] \mathbf{H}_{ik}^{\cdot\cdot}(\theta)$

  If all parameters but one appear linearly, then the model is flat

A classification of regression models (Pázman, 1993)



Density of the LS estimator (we suppose $\varepsilon \sim \mathscr{N}(\mathbf{0}, \sigma^2 \mathbf{I}_n)$)

Intrinsically linear models (in particular, repetitions at p points):

$\rightarrow$ exact distribution $\boxed{\hat{\theta}^n \sim q(\theta|\bar{\theta}) = \frac{n^{p/2} \det^{1/2} \mathbf{M}(\mathbf{X}_n, \theta)}{(2\pi)^{p/2} \sigma^p} \exp\left\{-\frac{1}{2\sigma^2} \|\boldsymbol{\eta}(\theta) - \boldsymbol{\eta}(\bar{\theta})\|^2\right\}}$

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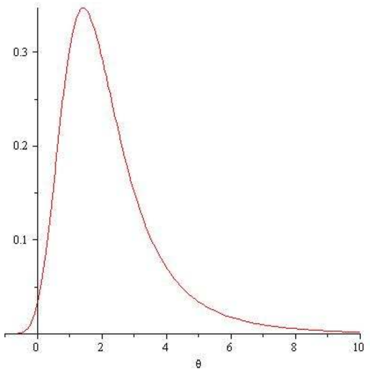
Ex: $\eta(x,\theta) = \exp(-\theta x)$, $\bar{\theta} = 2$, 15 observations at the same $x = 1/2$ ($\sigma^2 = 1$)



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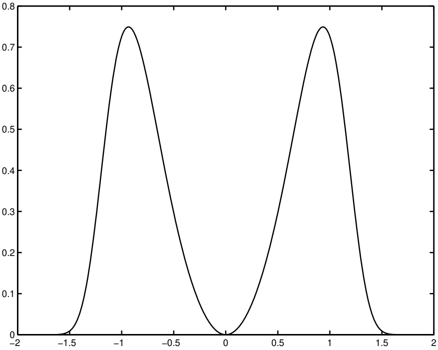
Ex: $\eta(x, \theta) = x\,\theta^3$, $\bar{\theta} = 0$, all observations at the same $x \neq 0$



Flat models: approximate density of $\hat{\theta}^n$

$$q(\theta|\bar{\theta}) = \frac{\det[\mathbf{Q}(\theta,\bar{\theta})]}{(2\pi)^{p/2}\,\sigma^p\,n^{p/2}\,\det^{1/2}\mathbf{M}(\mathbf{X}_n,\theta)}\ \exp\left\{-\frac{1}{2\sigma^2}\|\mathbf{P}_\theta[\boldsymbol{\eta}(\theta)-\boldsymbol{\eta}(\bar{\theta})]\|^2\right\}$$

where $\{\mathbf{Q}(\theta,\bar{\theta})\}_{ij} = \{n\,\mathbf{M}(\mathbf{X}_n,\theta)\}_{ij} + [\boldsymbol{\eta}(\theta)-\boldsymbol{\eta}(\bar{\theta})]^\top[\mathbf{I}_n-\mathbf{P}_\theta]\mathbf{H}_{ij}(\theta)$

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➠ Design of experiments? (since $q(\theta|\bar{\theta})$ depends on $\mathbf{X}_n$)

5 DOE based on small sample precision

(P & Pázman, 2013, Chap. 6)

1) Minimise the MSE $\mathrm{E}\{\|\hat{\theta}^n(\mathbf{y}) - \bar{\theta}\|^2\}$

The approximation of Clarke (1980) requires the 4th-order derivatives of $\boldsymbol{\eta}(\theta)$

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→ Minimise $\int_\Theta \|\theta - \bar{\theta}\|^2 q(\theta|\bar{\theta})\, \mathrm{d}\theta$ w.r.t. $\mathbf{X}_n$ using stochastic approximation

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Solution: approximate the density $\tilde{q}_w(\theta|\bar{\theta})$ of a penalised LS estimator $\tilde{\theta}^n$

$$\tilde{\theta}^n = \arg\min_\theta \left\{\|\mathbf{y} - \boldsymbol{\eta}(\theta)\|^2 + 2w(\theta)\right\}$$

where $w(\theta)$ forces θ to remain in Θ [$w(\theta) = +\infty$ outside Θ]

→ **Minimise** $\int_\Theta \|\theta - \bar{\theta}\|^2 \tilde{q}_w(\theta|\bar{\theta})\, \mathrm{d}\theta$ **w.r.t.** $\mathbf{X}_n$

[also covers the case of max. *a posteriori* estimation (relate $w(\theta)$ to the prior on θ)]

(P & Pázman, 1992; Pázman and Gauchi, 2006)

2) Use a small-sample variant of D-optimal design

A D-optimal design minimises

(*i*) the volume of asymptotic (ellipsoidal) confidence regions

(*ii*) the (Shannon) entropy of the asymptotic distribution of $\hat{\theta}^n$

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Hamilton and Watts (1985) minimize the (approximate) volume $V(\mathbf{X}_n, \theta^0)$ of (approximate) confidence regions ($V(\mathbf{X}_n, \theta^0)$ has an explicit form and a geometrical interpretation)

Vila (1990); Vila and Gauchi (2007) minimize the expected volume of exact confidence regions (not ellipsoidal, not necessarily of minimum volume), using stochastic approximation

→ Choose $\mathbf{X}_n$ that minimises the approximate entropy of the approximate distribution of $\hat{\theta}^n$ (P & Pázman, 1994b)

$$\text{Minimise } \mathrm{Ent}[q(\cdot|\bar{\theta})] = -\int_{\mathbb{R}^n} \log[q(\hat{\theta}^n(\mathbf{y})|\bar{\theta})]\varphi(\mathbf{y}|\mathbf{X}_n,\bar{\theta})\,\mathrm{d}\mathbf{y} \text{ w.r.t. } \mathbf{X}_n$$

where $\varphi(\mathbf{y}|\mathbf{X}_n,\bar{\theta})$ corresponds to $\mathbf{y} \sim \mathcal{N}(\boldsymbol{\eta}(\bar{\theta}), \sigma^2\mathbf{I}_n)$

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Use a 2nd order Taylor development of $\log[q(\hat{\theta}^n(\mathbf{y})|\bar{\theta})]$ around $\mathbf{y} = \boldsymbol{\eta}(\bar{\theta})$:

$$\mathrm{Ent}[q(\cdot|\bar{\theta})] = -\log q(\bar{\theta}|\bar{\theta}) - \frac{\sigma^2}{2}\sum_{i=1}^{N} \frac{\partial^2 \log q[\hat{\theta}(\mathbf{y})|\bar{\theta}]}{\partial y_i^2}\bigg|_{\boldsymbol{\eta}(\bar{\theta})} + \mathcal{O}(\sigma^4)$$

After some (lengthy) calculations...

$$\mathrm{Ent}[q(\cdot|\bar{\theta})] = \overbrace{\frac{p}{2}[1+\log(2\pi\sigma^2)] - \frac{1}{2}\log\det[n\mathbf{M}(\mathbf{X}_n,\bar{\theta})]}^{\text{entropy of asymptotic normal distribution}}$$
$$- \frac{\sigma^2}{2n}\sum_{h,i,j,k=1}^{p}\left(\{\mathbf{M}^{-1}(\mathbf{X}_n,\bar{\theta})\}_{ij}\left[\frac{1}{n}\{\mathbf{M}^{-1}(\mathbf{X}_n,\bar{\theta})\}_{kh}[R_{kjhi}(\bar{\theta}) + U^h_{kij}(\bar{\theta})]\right.\right.$$
$$\left.\left. - G^h_{ki}(\bar{\theta})\,G^k_{hj}(\bar{\theta}) - G^k_{kh}(\bar{\theta})\,G^h_{ij}(\bar{\theta})\right]\right) + \mathcal{O}(\sigma^4)$$

$$\text{where } U^h_{kij}(\theta) = \frac{\partial^3\boldsymbol{\eta}^\top(\theta)}{\partial\theta_k\partial\theta_i\partial\theta_j}\,\frac{\partial\boldsymbol{\eta}(\theta)}{\partial\theta_h}$$
$$G^k_{ij}(\theta) = \frac{1}{n}\sum_{h=1}^{p}\frac{\partial\boldsymbol{\eta}^\top(\theta)}{\partial\theta_h}\,\mathbf{H}_{\boldsymbol{\cdot}ij}\,\{\mathbf{M}^{-1}(\mathbf{X}_n,\bar{\theta})\}_{hk}$$

with $R_{hijk}(\theta) = T_{hjik}(\theta) - T_{hkij}(\theta)$, $T_{hjik}(\theta) = [\mathbf{H}_{\boldsymbol{\cdot}hj}(\theta)]^\top[\mathbf{I}_n - \mathbf{P}_\theta]\mathbf{H}_{\boldsymbol{\cdot}ik}(\theta)$ and $\mathbf{H}_{\boldsymbol{\cdot}ij}(\theta) = \frac{\partial^2\boldsymbol{\eta}(\theta)}{\partial\theta_i\partial\theta_j}$

3) Related work using the approximate density $q(\theta|\bar{\theta})$

3a) (approximate) marginal densities of $\hat{\theta}^n$ (Pázman & P, 1996)

Denote $\gamma = h(\theta)$ [with $\gamma = \theta_i$ for some $i \in \{1, \ldots, p = \dim(\theta)\}$ as particular case]

$$q(\gamma|\bar{\theta}) = \frac{1}{\sqrt{2\pi}\sigma \|\mathbf{b}_\gamma\|} \exp\left\{-\frac{1}{2\sigma^2}\|\mathbf{P}_\gamma[\boldsymbol{\eta}(\theta_\gamma) - \boldsymbol{\eta}(\bar{\theta})]\|^2\right\}$$

where

$$\begin{aligned}
\theta_\gamma &= \arg\min_{\theta: h(\theta)=\gamma} \|\boldsymbol{\eta}(\theta) - \boldsymbol{\eta}(\bar{\theta})\|^2 \\
\mathbf{b}_\gamma &= \frac{1}{n} \frac{\partial \boldsymbol{\eta}(\theta)}{\partial \theta^\top}\Big|_{\theta_\gamma} \mathbf{M}^{-1}(\mathbf{X}_n, \theta_\gamma) \frac{\partial h(\theta)}{\partial \theta}\Big|_{\theta_\gamma} \\
\mathbf{P}_\gamma &= \frac{\mathbf{b}_\gamma \mathbf{b}_\gamma^\top}{\|\mathbf{b}_\gamma\|^2}
\end{aligned}$$

[There also exist more precise approximations, more complicated;
the difficulty compared to (Tierney et al., 1989) is that $\hat{\theta}^n(\mathbf{y})$ is not known explicitly]

→ Can be used to compare experiments

Ex: a two-compartment model in pharmacokinetics (P & Pázman, 2001)
Observe $y(t) = x_C(t)/V + \varepsilon(t)$ where $x_C(t)$ evolves according to

$$\begin{cases} \frac{dx_C(t)}{dt} = (-K_{EL} - K_{CP})x_C(t) + K_{PC}x_P(t) + u(t) \\ \frac{dx_P(t)}{dt} = K_{CP}x_C(t) - K_{PC}x_P(t) \end{cases}$$

errors $\epsilon(t_i)$ i.i.d. $\mathscr{N}(0, \sigma^2)$

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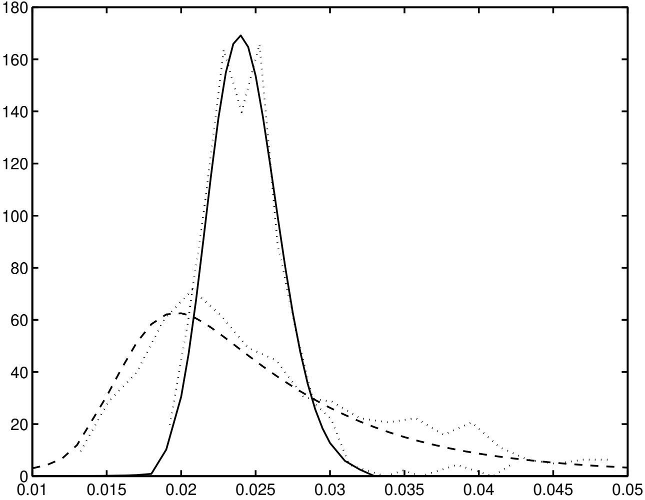
$$\begin{cases} \frac{dx_C(t)}{dt} = (-K_{EL} - K_{CP})x_C(t) + K_{PC}x_P(t) + u(t) \\ \frac{dx_P(t)}{dt} = K_{CP}x_C(t) - K_{PC}x_P(t) \end{cases}$$

errors $\epsilon(t_i)$ i.i.d. $\mathscr{N}(0, \sigma^2)$

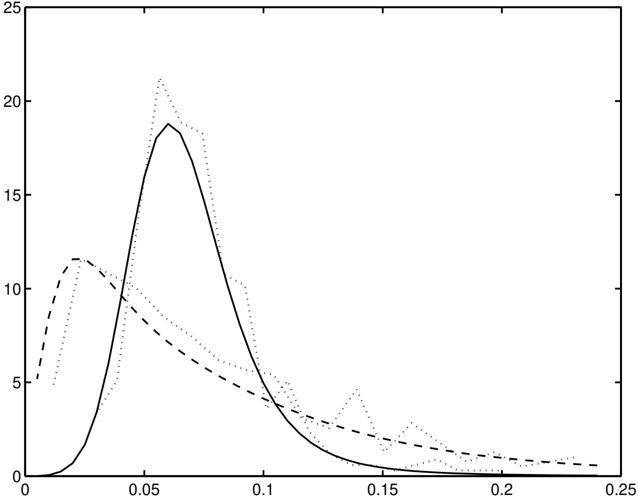
➔ 4 unknown parameters $\theta = (K_{CP}, K_{PC}, K_{EL}, V)^\top$

Compare 2 designs (8 observation times each) using simulated experiments with a given true $\bar{\theta}$

$\hat{K}_{EL}$ [$\bar{K}_{EL} = 0.0242$]



$\hat{K}_{CP}$ $[\bar{K}_{CP} = 0.066]$



3b) Bias correction for LS estimation in nonlinear regression

$$\mathbf{b}(\bar{\theta}) = \text{bias of } \hat{\theta}^n = \mathsf{E}_{\mathbf{X}_n,\bar{\theta}}\{\hat{\theta}^n(\mathbf{y})\} - \bar{\theta}$$

$$= \underbrace{-\frac{\sigma^2}{2n^2}\,\mathbf{M}^{-1}(\mathbf{X}_n,\bar{\theta})\,\frac{\partial\boldsymbol{\eta}^\top(\theta)}{\partial\theta}\Big|_{\bar{\theta}}\,\sum_{i,j=1}^{p}\mathbf{H}_{ij}(\bar{\theta})\,\{\mathbf{M}^{-1}(\mathbf{X}_n,\bar{\theta})\}_{ij}}_{=\tilde{\mathbf{b}}(\bar{\theta})\ \text{(Box, 1971)}} + \mathcal{O}(\sigma^4)$$

We can write $\hat{\theta}^n = \mathbf{b}(\bar{\theta}) + \bar{\theta} + \omega$, with $\mathsf{E}_{\mathbf{X}_n,\bar{\theta}}\{\omega\} = \mathbf{0}$

Two-stage LS: solve $\boxed{\hat{\theta}^n = \mathbf{b}(\theta) + \theta}$ for $\theta \rightarrow \hat{\theta}^{n,*}$

[$\hat{\theta}^{n,*}$ unbiased when $\mathbf{b}(\theta) = \mathbf{A}\theta + \mathbf{c}$ for all θ with $\mathbf{I}_p + \mathbf{A}$ nonsingular]

1st method: $\hat{\theta}^{n,0} = \hat{\theta}^n$ given, then

$$\hat{\theta}^{n,1} = \hat{\theta}^n - \mathbf{b}(\hat{\theta}^{n,0})$$

[. . . sometimes more biased than $\hat{\theta}^n$ (Picard and Prum, 1992)]

1st method: $\hat{\theta}^{n,0} = \hat{\theta}^n$ given, then

$$\begin{aligned}
\hat{\theta}^{n,1} &= \hat{\theta}^n - \mathbf{b}(\hat{\theta}^{n,0}) \\
&\quad [\ldots \text{sometimes more biased than } \hat{\theta}^n \text{ (Picard and Prum, 1992)}] \\
\hat{\theta}^{n,2} &= \hat{\theta}^n - \mathbf{b}(\hat{\theta}^{n,1}) \\
\vdots &= \vdots \\
\hat{\theta}^{n,*} = \hat{\theta}^{n,\infty} &= \hat{\theta}^n - \mathbf{b}(\hat{\theta}^{n,\infty})
\end{aligned}$$

that is, $\hat{\theta}^{n,*} + \mathbf{b}(\hat{\theta}^{n,*}) = \hat{\theta}^n$, or

$$\mathsf{E}_{\mathbf{X}_n,\hat{\theta}^{n,*}}\{\hat{\theta}^n(\mathbf{y})\} = \boxed{\int_{\mathbb{R}^n} \hat{\theta}^n(\mathbf{y})\, \varphi(\mathbf{y}|\mathbf{X}_n, \hat{\theta}^{n,*})\, \mathrm{d}\mathbf{y} = \hat{\theta}^n}$$

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Solve for $\hat{\theta}^{n,*}$ using stochastic approximation (P & Pázman, 1994a)

2nd method (approximate): use $\tilde{\mathbf{b}}$ instead of $\mathbf{b}$

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Solve for $\tilde{\theta}^{n,*}$: $\boxed{\tilde{\theta}^{n,*} + \tilde{\mathbf{b}}(\tilde{\theta}^{n,*}) = \hat{\theta}^n}$

that is

$$\tilde{\theta}^{n,*} - \frac{\sigma^2}{2n^2}\,\mathbf{M}^{-1}(\mathbf{X}_n, \tilde{\theta}^{n,*})\,\frac{\partial \boldsymbol{\eta}^\top(\theta)}{\partial \theta}\Big|_{\tilde{\theta}^{n,*}} \sum_{i,j=1}^{p} \mathbf{H}_{:ij}(\tilde{\theta}^{n,*})\,\{\mathbf{M}^{-1}(\mathbf{X}_n, \tilde{\theta}^{n,*})\}_{ij} = \hat{\theta}^n$$

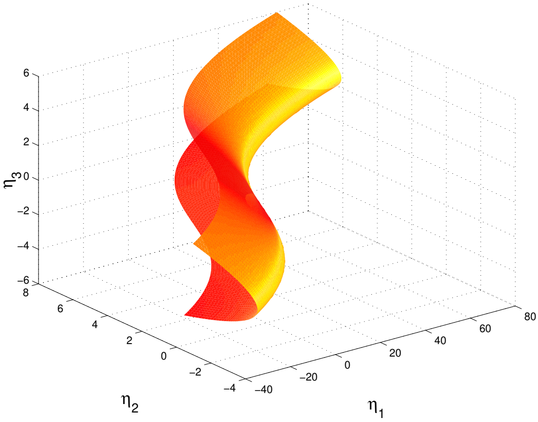
[Different from the score-corrected estimator $\hat{\theta}^n_{sc}$ of (Firth, 1993):

→ solve $\boxed{\frac{\partial \boldsymbol{\eta}^\top(\theta)}{\partial \theta}[\mathbf{y} - \boldsymbol{\eta}(\theta)] - \mathbf{M}(\mathbf{X}_n, \theta)\tilde{\mathbf{b}}(\theta) = \mathbf{0}}$ for θ]

(Pázman & P, 1998) gives the (approximate) joint and marginal densities of $\tilde{\theta}^{n,*}$ and $\hat{\theta}^n_{sc}$

6 Extended optimality criteria

(P & Pázman, 2013, Chap. 7)



$\mathbb{S}_\eta$ may overlap, there may be local minimisers for the LS problem...

Important and difficult problem, often neglected

What can we do at the design stage?

➠ extensions of usual optimality criteria

➔ Avoid situations where $\|\boldsymbol{\eta}(\theta) - \boldsymbol{\eta}(\bar{\theta})\|$ can be small when $\|\theta - \bar{\theta}\|$ is large:

$$\text{maximise } \phi_{eE}(\mathbf{X}_n, \theta^0) = \min_{\theta} \frac{\|\boldsymbol{\eta}(\theta) - \boldsymbol{\eta}(\theta^0)\|^2}{\|\theta - \theta^0\|^2}$$

corresponds to E-optimal design ($\Leftrightarrow$ maximise $\lambda_{\min}[\mathbf{M}(\mathbf{X}_n)]$) when η is linear

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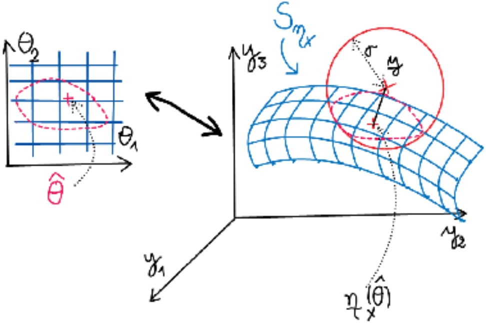
Extensions to generalised regression models and other design criteria in the Ph.D. thesis (Sternmüllerová, 2019)

7 Nonlocal DoE for nonlinear models

(P & Pázman, 2013, Chap. 8)

Nonlinear regression



Nonlinear model ➠ **everything is local**

7 Nonlocal DoE for nonlinear models

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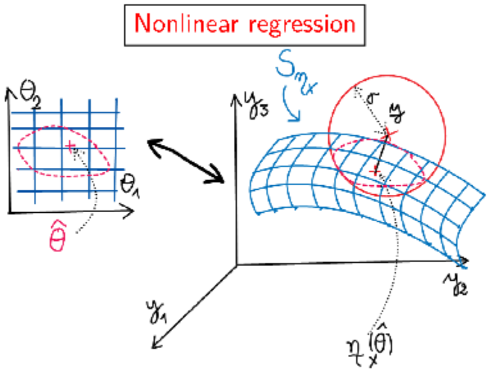

Nonlinear model ➠ **everything is local**

$\phi(\cdot)$ an information criterion, to be maximised with respect to the design $\mathbf{X}_n$:

$$\phi(\mathbf{X}_n) = \phi(\mathbf{X}_n, \theta), \text{ but which } \theta?$$

Local optimum design: based on a nominal value $\theta^0 \rightarrow$ maximize $\phi(\mathbf{X}_n, \theta^0)$
[concerns all methods considered so far,
based on asymptotic normality (AN) or small-sample properties]

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Objective of nonlocal DoE: remove the dependence in θ^0

3 main classes, essentially for $\phi(\xi, \theta) = \Phi[\mathbf{M}(\mathbf{X}_n, \theta)]$ (based on AN)

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➠ Between ❶ and ❷: regularised maximin criteria, quantiles and probability level criteria

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❸ Sequential design

❶ Average Optimum design

Probability measure $\mu(\mathrm{d}\theta)$ on $\Theta \subseteq \mathbb{R}^p$ ($\neq$ Bayesian estimation)

$$\boxed{\phi(\cdot,\theta^0) \rightarrow \phi_A(\cdot) = \int_\Theta \phi(\cdot,\theta)\,\mu(\mathrm{d}\theta)}$$

[No difficulty if Θ is finite and $\mu = \sum_{i=1}^M \alpha_i \delta_\theta^{(i)}$ (integral $\rightarrow$ finite sum);
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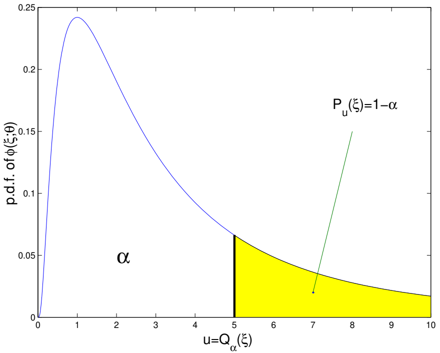
Problems

❶ Optimal design for $\phi_A(\cdot)$ not invariant by a monotone transformation of $\phi(\cdot, \theta)$

❷ Optimal design for $\phi_M(\cdot)$ very sensitive to the choice of the boundary of Θ

Between ❶ and ❷: quantiles and probability level criteria



➞ maximise P_u for a given u, or maximise Q_α for a given α

(when $\alpha \to 0$, tends to maximin optimality)

Directional derivatives, algorithms . . . but the criteria are not concave:

→ no guarantee of successful maximisation

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A related very promising approach: maximise the conditional value at risk (or superquantile) as proposed by Valenzuela et al. (2015)

$$\phi_\alpha(\mathbf{X}_n) = \max_{t\in\mathbb{R}} \left\{ t + \frac{1}{\alpha} \int_\Theta \min\left[0, \phi(\mathbf{X}_n;\theta) - t\right] \mu(\mathrm{d}\theta) \right\}$$

When μ has a density (w.r.t. Lebesgue measure on Θ) then

$$\phi_\alpha(\mathbf{X}_n) = \frac{1}{\alpha} \int_{\{\theta:\phi(\mathbf{X}_n;\theta)<Q_\alpha(\mathbf{X}_n)\}} \phi(\mathbf{X}_n;\theta)\,\mu(\mathrm{d}\theta)$$

$\phi(\xi,\theta)$ concave in $\xi \Rightarrow \phi_\alpha(\xi)$ concave
$\phi_1(\mathbf{X}_n) = \phi_A(\mathbf{X}_n)$ and $\phi_\alpha(\mathbf{X}_n) \to \phi_M(\mathbf{X}_n)$ as $\alpha \to 0$
[part of the Ph.D. thesis (Sternmüllerová, 2019)]

❸ Sequential design

$$\theta^0 \to \text{design: } \mathbf{X}^1 = \arg\max_{\mathbf{X}} \phi(\mathbf{X}, \theta^0)$$
$$\to \text{observe: } \mathbf{y}^1 = \mathbf{y}^1(\mathbf{X}^1)$$
$$\to \text{estimate: } \hat{\theta}^1 = \arg\min_\theta LS(\theta; \mathbf{y}^1, \mathbf{X}^1)$$
$$\to \text{design: } \mathbf{X}^2 = \arg\max_{\mathbf{X}} \phi(\{\mathbf{X}^1, \mathbf{X}\}, \hat{\theta}^1)$$
$$\to \text{observe: } \mathbf{y}^2 = \mathbf{y}^2(\mathbf{X}^2)$$
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$$\to \text{design: } \mathbf{X}^3 = \arg\max_{\mathbf{X}} \phi(\{\mathbf{X}^1, \mathbf{X}^2, \mathbf{X}\}, \hat{\theta}^2)$$

...etc.

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. . . etc.

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(there exist variants with Bayesian estimation and average optimality)

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$$\ldots \text{etc.}$$

➞ Replace unknown θ by best current guess $\hat{\theta}^k$
(there exist variants with Bayesian estimation and average optimality)

Consistency of $\hat{\theta}^n$? Asymptotic normality (for designs based on **M**)?
(difficulty: $\mathbf{X}^k$ depends on $\mathbf{y}^1, \ldots, \mathbf{y}^{k-1} \Longrightarrow$ independence is lost)

Each $\mathbf{X}^i$ has size q

➠ No big difficulty if $q \geq p = \dim(\theta)$ (batch sequential design)

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When

$$\mathbf{M}(\mathbf{X}_{k+1}, \hat{\theta}^k) = \frac{k}{k+1}\mathbf{M}(\mathbf{X}_k, \hat{\theta}^k) + \frac{1}{k+1}\frac{\partial \eta(x_{k+1}, \theta)}{\partial \theta}\Big|_{\hat{\theta}^k}\frac{\partial \eta(x_{k+1}, \theta)}{\partial \theta^\top}\Big|_{\hat{\theta}^k}$$

with $x_{k+1} = \arg\max_{\mathscr{X}} \underbrace{F_\phi(\xi^k; \delta_x|\hat{\theta}^k)}_{\text{directional derivative}}$ $\Leftrightarrow$ conditional gradient algorithm with step-size $\frac{1}{k+1}$ (Wynn, 1970)

➤ some CV results for Bayesian estimation (Hu, 1998)

➤ no general CV results for LS and ML estimation,

[unless $\mathscr{X} = \{x^{(1)}, \ldots, x^{(\ell)}\}$ finite (P 2009, 2010)]

8 Conclusions

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  check closeness to θ^1 (plot marginals),
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Thank you for your attention !

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