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Applications of Gaussian process priors

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Applications from my own work
Agenda

- Optimal treatment assignment in experiments.
  - Setting: Treatment assignment given baseline covariates
  - General decision theory result:
    Non-random rules dominate random rules
  - Prior for expectation of potential outcomes given covariates
  - Expression for MSE of estimator for ATE
    to minimize by treatment assignment
- Optimal insurance and taxation.
  - Review: Envelope theorem.
  - Economic setting: Co-insurance rate for health insurance
  - Statistical setting: prior for behavioral average response function
  - Expression for posterior expected social welfare
    to maximize by choice of co-insurance rate

Applications use Gaussian process priors

1. Optimal experimental design
   - How to assign treatment to minimize mean squared error for treatment effect estimators?
   - Gaussian process prior for the conditional expectation of potential outcomes given covariates.
2. Optimal insurance and taxation
   - How to choose a co-insurance rate or tax rate to maximize social welfare, given (quasi-)experimental data?
   - Gaussian process prior for the behavioral response function mapping the co-insurance rate into the tax base.

Application 1
"Why experimenters might not always want to randomize"
Setup

1. *Sampling:*
   random sample of n units
   baseline survey $\Rightarrow$ vector of covariates X_i
2. *Treatment assignment:*
   binary treatment assigned by $D_i = d_i(\boldsymbol{X}, U)$
   $\boldsymbol{X}$ matrix of covariates; U randomization device
3. *Realization of outcomes:*
   $Y_i = D_i Y_i^1 + (1 - D_i) Y_i^0$
4. *Estimation:*
   estimator $\widehat{\beta}$ of the (conditional) average treatment effect,
   $\beta = \frac{1}{n} \sum_i E[Y_i^1 - Y_i^0 | X_i, \theta]$

Questions

- How should we assign treatment?
- In particular, if X_i has continuous or many discrete components?
- How should we estimate β?
- What is the role of prior information?

Some intuition

- "Compare apples with apples"
  $\Rightarrow$ balance covariate distribution.
- Not just balance of means!
- We don't add random noise to estimators
  – why add random noise to experimental designs?
- Identification requires controlled trials (CTs),
  but not randomized controlled trials (RCTs).

General decision problem allowing for randomization

- General decision problem:
  - State of the world θ, observed data X, randomization device $U \perp X$,
  - decision procedure $\delta(X, U)$, loss $L(\delta(X, U), \theta)$.
- Conditional expected loss of decision procedure $\delta(X, U)$:

$$R(\delta, \theta | U = u) = E[L(\delta(X, u), \theta) | \theta]$$

- Bayes risk:

$$R^B(\delta, \pi) = \int \int R(\delta, \theta | U = u) d\pi(\theta) dP(u)$$

- Minimax risk:

$$R^{mm}(\delta) = \int \max_\theta R(\delta, \theta | U = u) dP(u)$$

Theorem (Optimality of deterministic decisions)

Consider a general decision problem.
Let R^* equal R^B or R^{mm}. Then:

1. *The optimal risk $R^*(\delta^*)$, when considering only deterministic procedures $\delta(X)$, is no larger than the optimal risk when allowing for randomized procedures $\delta(X,U)$.*
2. *If the optimal deterministic procedure δ^* is unique, then it has strictly lower risk than any non-trivial randomized procedure.*

Practice problem

Proof this.

Hints:

- Assume for simplicity that U has finite support.
- Note that a (weighted) average of numbers is always at least as large as their minimum.
- Write the risk (Bayes or minimax) of any randomized assignment rule as (weighted) average of the risk of deterministic rules.

Solution

- Any robability distribution $P(u)$ satisfies
  - $\sum_u P(u) = 1$, $P(u) \geq 0$ for all u.
  - Thus $\sum_u R_u \cdot P(u) \geq \min_u R_u$ for any set of values R_u.
- Let $\delta^u(x) = \delta(x, u)$.
- Then

$$R^B(\delta, \pi) = \sum_u \int R(\delta^u, \theta) d\pi(\theta) P(u)$$

$$\geq \min_u \int R(\delta^u, \theta) d\pi(\theta) = \min_u R^B(\delta^u, \pi).$$

- Similarly

$$R^{mm}(\delta) = \sum_u \max_\theta R(\delta^u, \theta) P(u)$$

$$\geq \min_u \max_\theta R(\delta^u, \theta) = \min_u R^{mm}(\delta^u).$$

Bayesian setup

- Back to experimental design setting.
- Conditional distribution of potential outcomes: for $d = 0, 1$

$$Y_i^d | X_i = x \sim N(f(x,d), \sigma^2).$$

- Gaussian process prior:

$$\begin{aligned} f &\sim GP(\mu, C), \\ E[f(x,d)] &= \mu(x,d) \\ \mathrm{Cov}(f(x_1,d_1), f(x_2,d_2)) &= C((x_1,d_1),(x_2,d_2)) \end{aligned}$$

- Conditional average treatment effect (CATE):

$$\beta = \frac{1}{n} \sum_i E[Y_i^1 - Y_i^0 | X_i, \theta] = \frac{1}{n} \sum_i f(X_i, 1) - f(X_i, 0).$$

Notation:

- Covariance matrix C, where $C_{i,j} = C((X_i, D_i), (X_j, D_j))$
- Mean vector μ, components $\mu_i = \mu(X_i, D_i)$
- Covariance of observations with CATE,

$$\begin{aligned}\overline{C}_i &= \mathrm{Cov}(Y_i, \beta | \boldsymbol{X}, \boldsymbol{D}) \\ &= \frac{1}{n} \sum_j \left(C((X_i, D_i), (X_j, 1)) - C((X_i, D_i), (X_j, 0)) \right).\end{aligned}$$

Practice problem

- Derive the posterior expectation $\widehat{\beta}$ of β.
- Derive risk of any deterministic treatment assignment vector $\boldsymbol{d}$, assuming
  1. The estimator $\widehat{\beta}$ is used.
  2. The loss function $(\widehat{\beta} - \beta)^2$ is considered.

Solution

- The posterior expectation $\widehat{\beta}$ of β equals

$$\widehat{\beta} = \mu_\beta + \overline{C}' \cdot (C + \sigma^2 I)^{-1} \cdot (\boldsymbol{Y} - \mu).$$

- The corresponding risk equals

$$\begin{aligned} R^B(\mathbf{d}, \widehat{\beta} | \boldsymbol{X}) &= \mathrm{Var}(\beta | \boldsymbol{X}, \boldsymbol{Y}) \\ &= \mathrm{Var}(\beta | \boldsymbol{X}) - Var(E[\beta | \boldsymbol{X}, \boldsymbol{Y}] | \boldsymbol{X}) \\ &= \mathrm{Var}(\beta | \boldsymbol{X}) - \overline{C}' \cdot (C + \sigma^2 I)^{-1} \cdot \overline{C}. \end{aligned}$$

Discrete optimization

- The optimal design solves

$$\max_{\mathbf{d}} \overline{C}' \cdot (C + \sigma^2 I)^{-1} \cdot \overline{C}.$$

- Possible optimization algorithms:
  1. Search over random **d**
  2. greedy algorithm
  3. simulated annealing

Variation of the problem

Practice problem

- Suppose that the researcher insists on estimating β using a simple comparison of means,

$$\widehat{\beta} = \frac{1}{n_1}\sum_i D_i Y_i - \frac{1}{n_0}\sum_i (1 - D_i) Y_i.$$

- Derive again the risk of any deterministic treatment assignment vector $\boldsymbol{d}$, assuming
  1. The estimator $\widehat{\beta}$ is used.
  2. The loss function $(\widehat{\beta} - \beta)^2$ is considered.

Solution

- Notation:
  - Let $\mu_i^d = \mu(X_i, d)$ and $C_{i,j}^{d^1,d^2} = C((X_i, d^1), (X_j, d^2))$.
  - Collect these terms in the vectors μ^d and matrices C^{d^1,d^2}, and let $\widetilde{\mu} = (\mu^1, \mu^2)$, $\widetilde{C} = \begin{pmatrix} C^{00} & C^{01} \\ C^{10} & C^{11} \end{pmatrix}$.
  - Weights

$$
\begin{aligned}
w &= (w^0, w^1), \\
w_i^1 &= \tfrac{d_i}{n_1} - \tfrac{1}{n}, \\
w_i^0 &= -\tfrac{1-d_i}{n_0} + \tfrac{1}{n}.
\end{aligned}
$$

- Risk: Sum of variance and squared bias,

$$
R^B(\mathbf{d}, \widehat{\beta} | \boldsymbol{X}) = \sigma^2 \cdot \left[\frac{1}{n_1} + \frac{1}{n_0} \right] + \left(w' \cdot \widetilde{\mu} \right)^2 + w' \cdot \widetilde{C} \cdot w.
$$

Special case linear separable model

- Suppose

$$f(x,d) = x' \cdot \gamma + d \cdot \beta,$$
$$\gamma \sim N(0,\Sigma),$$

  and we estimate β using comparison of means.
- Bias of $\widehat{\beta}$ equals $(\overline{X}^1 - \overline{X}^0)' \cdot \gamma$, prior expected squared bias

$$(\overline{X}^1 - \overline{X}^0)' \cdot \Sigma \cdot (\overline{X}^1 - \overline{X}^0).$$

- Mean squared error

$$MSE(d_1,\ldots,d_n) = \sigma^2 \cdot \left[\frac{1}{n_1} + \frac{1}{n_0}\right] + (\overline{X}^1 - \overline{X}^0)' \cdot \Sigma \cdot (\overline{X}^1 - \overline{X}^0).$$

- $\Rightarrow$Risk is minimized by
  1. choosing treatment and control arms of equal size,
  2. and optimizing balance as measured by the difference in covariate means $(\overline{X}^1 - \overline{X}^0)$.

Review for application 2: The envelope theorem

- Policy parameter t
- Vector of individual choices x
- Choice set $\mathscr{X}$
- Individual utility $\upsilon(x,t)$
- Realized choices

$$x(t) \in \underset{x \in \mathscr{X}}{\operatorname{argmax}} \; \upsilon(x,t).$$

- Realized utility

$$V(t) = \max_{x \in \mathscr{X}} \upsilon(x,t) = \upsilon(x(t),t)$$

- Let $x^* = x(t^*)$ for some fixed t^*
- Define

$$\begin{aligned}\tilde{V}(t) &= V(t) - \upsilon(x^*, t) \qquad (1)\\ &= \upsilon(x(t), t) - \upsilon(x(t^*), t)\\ &= \max_{x \in \mathscr{X}} \upsilon(x, t) - \upsilon(x^*, t). \qquad (2)\end{aligned}$$

- Definition of $\tilde{V}$ immediately implies:
  - $\tilde{V}(t) \geq 0$ for all t and $\tilde{V}(t^*) = 0$.
  - Thus: t^* is a global minimizer of $\tilde{V}$.
- If $\tilde{V}$ is differentiable at t^*: $\tilde{V}'(t^*) = 0$
- Thus

$$V'(t^*) = \frac{\partial}{\partial t} \upsilon(x^*, t)|_{t=t^*},$$

- Behavioral responses don't matter for effect of policy change on individual utility!

Application 2
"Optimal insurance and taxation using machine learning"
Economic setting

- Population of insured individuals i.
- Y_i: health care expenditures of individual i.
- T_i: share of health care expenditures covered by the insurance
  $1 - T_i$: coinsurance rate; $Y_i \cdot (1 - T_i)$: out-of-pocket expenditures
- Behavioral response to share covered: structural function

$$Y_i = g(T_i, \varepsilon_i).$$

- Per capita expenditures under policy t: average structural function

$$m(t) = E[g(t, \varepsilon_i)].$$

Policy objective

- Insurance provider's expenditures per person: $t \cdot m(t)$.
  - Mechanical effect of increase in t (accounting):
$$m(t)dt.$$
  - Behavioral effect of increase in t (key empirical challenge):
$$t \cdot m'(t)dt.$$
- Utility of the insured:
  - Mechanical effect of increase in t (accounting):
$$m(t)dt.$$
  - Behavioral effect: None, by envelope theorem.
  - $\Rightarrow$ effect on utility = equivalent variation = mechanical effect
- Assign relative value $\lambda > 1$ to a marginal dollar for the sick vs. the insurer.

Practice problem

- Write the effect $u'(t)$ on social welfare u of an increase in t as a sum of mechanical and behavioral effects on individual welfare and insurer revenues.
- Set $u(0) = 0$ and integrate to obtain an expression for social welfare.

Solution

- Marginal effect of a change in t on social welfare:

$$u'(t) = (\lambda - 1) \cdot m(t) - t \cdot m'(t) = \lambda m(t) - \frac{\partial}{\partial t}(t \cdot m(t)). \tag{3}$$

- Integrating and imposing the normalization $u(0) = 0$:

$$u(t) = \lambda \int_0^t m(x)dx - t \cdot m(t). \tag{4}$$

- Special case $\lambda = 1$: “Harberger triangle” (not the relevant case)

Observed data and prior

- n i.i.d. draws of (Y_i, T_i)
- T_i was randomly assigned in an experiment, so that $T_i \perp \varepsilon_i$, and

$$E[Y_i | T_i = t] = E[g(t, \varepsilon_i) | T_i = t] = E[g(t, \varepsilon_i)] = m(t).$$

- Y_i is normally distributed given T_i,

$$Y_i | T_i = t \sim N(m(t), \sigma^2).$$

- Gaussian process prior for $m(\cdot)$,

$$m(\cdot) \sim GP(\mu(\cdot), C(\cdot, \cdot)).$$

Practice problem

- What is the prior distribution of $u(t) = \lambda \int_0^t m(x)dx - t \cdot m(t)$?
- What is the prior covariance of $u(t)$ and $\boldsymbol{Y}$ given $\boldsymbol{T}$?
- What is the posterior expectation of $u(t)$ given $\boldsymbol{Y}$ and $\boldsymbol{T}$?

Solution

- Linear functions of normal vectors are normal.
- Linear operators of Gaussian processes are Gaussian processes.
- Prior moments:

$$\begin{aligned} \nu(t) = E[u(t)] &= \lambda \int_0^t \mu(x)dx - t\cdot\mu(t), \\ D(t,t') = \mathrm{Cov}(u(t), m(t'))) &= \lambda\cdot\int_0^t C(x,t')dx - t\cdot C(t,t'), \\ \mathrm{Var}(u(t)) &= \lambda^2\cdot\int_0^t\int_0^t C(x,x')dx'dx \\ &\quad - 2\lambda t\cdot\int_0^t C(x,t)dx + t^2\cdot C(t,t). \end{aligned}$$

- Covariance with data:

$$\boldsymbol{D}(t) = \mathrm{Cov}(u(t), \boldsymbol{Y}|\boldsymbol{T}) = \mathrm{Cov}(u(t), (m(T_1), \ldots, m(T_n))|\boldsymbol{T})$$
$$= (D(t, T_1), \ldots, D(t, T_n)).$$

- Posterior expectation of $u(t)$:

$$\begin{aligned}\widehat{u}(t) &= E[u(t)|\boldsymbol{Y}, \boldsymbol{T}] \\ &= E[u(t)|\boldsymbol{T}] + \mathrm{Cov}(u(t), \boldsymbol{Y}|\boldsymbol{T}) \cdot \mathrm{Var}(\boldsymbol{Y}|\boldsymbol{T})^{-1} \cdot (\boldsymbol{Y} - E[\boldsymbol{Y}|\boldsymbol{T}]) \\ &= \nu(t) + \boldsymbol{D}(t) \cdot \left[\boldsymbol{C} + \sigma^2 \boldsymbol{I}\right]^{-1} \cdot (\boldsymbol{Y} - \mu).\end{aligned}$$

Optimal policy choice

- Bayesian policy maker aims to maximize expected social welfare (note: different from expectation of maximizer of social welfare!)
- Thus
$$\widehat{t^*} = \widehat{t^*}(\boldsymbol{Y}, \boldsymbol{T}) \in \underset{t}{\operatorname{argmax}}\ \widehat{u}(t).$$
- First order condition
$$\begin{aligned}\frac{\partial}{\partial t}\widehat{u}(\widehat{t^*}) &= E[u'(\widehat{t^*})|\boldsymbol{Y}, \boldsymbol{T}] \\ &= v'(\widehat{t^*}) + \boldsymbol{B}(\widehat{t^*}) \cdot \left[\boldsymbol{C} + \sigma^2 \boldsymbol{I}\right]^{-1} \cdot (\boldsymbol{Y} - \mu) = 0,\end{aligned}$$
where $\boldsymbol{B}(t) = (B(t, T_1), \ldots, B(t, T_n))$ and
$$\begin{aligned}B(t, t') &= \mathrm{Cov}\left(\frac{\partial}{\partial t}u(t), m(t')\right) = \frac{\partial}{\partial t}D(t, t') \\ &= (\lambda - 1) \cdot C(t, t') - t \cdot \frac{\partial}{\partial t}C(t, t').\end{aligned}$$

Production objective

- Another important class of policy problems:
- Observable outcome Y_i (e.g. student test scores)
- Input vector $T_i \in \mathbb{R}^{d_t}$ (e.g., teachers per student, ...)
- (educational) production function

$$Y_i = g(T_i, \varepsilon_i).$$

- Policy maker's objective is to maximize average (expected) outcomes $E[Y_i]$ across schools, net of the cost of inputs.
- Unit-price of input j: p_j.
- Willingness to pay for a unit-increase in Y: λ

- Yields the objective function

$$u(t) = \lambda \cdot m(t) - p \cdot t.$$

- Same type of data and prior as before.
- Posterior expectation:

$$\begin{aligned}
\widehat{u}(t) &= \nu(t) + \boldsymbol{D}(t) \cdot \left[\boldsymbol{C} + \sigma^2 \boldsymbol{I}\right]^{-1} \cdot (\boldsymbol{Y} - \mu), \\
\nu(t) &= \lambda \cdot \mu(t) - p \cdot t, \\
D(t, t') &= \lambda \cdot \boldsymbol{C}(t, t').
\end{aligned}$$

- First order condition:

$$\widehat{u}'(\widehat{t^*}) = \nu'(\widehat{t^*}) + \boldsymbol{B}(\widehat{t^*}) \cdot \left[\boldsymbol{C} + \sigma^2 \boldsymbol{I}\right]^{-1} \cdot (\boldsymbol{Y} - \mu) = 0.$$

where now $B(t, t') = \lambda \cdot \frac{\partial}{\partial t} \boldsymbol{C}(t, t')$.

The RAND health insurance experiment

- (cf. Aron-Dine et al., 2013)
- Between 1974 and 1981
  representative sample of 2000 households
  in six locations across the US
- families randomly assigned to
  plans with one of six consumer coinsurance rates
- 95, 50, 25, or 0 percent
  2 more complicated plans (we drop those)
- Additionally: randomized Maximum Dollar Expenditure limits
  5, 10, or 15 percent of family income,
  up to a maximum of $750 or $1,000
  (we pool across those)

Table: Expected spending for different coinsurance rates

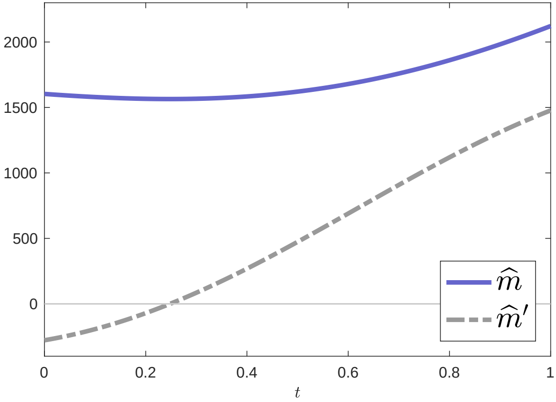
	(1) Share with any	(2) Spending in $	(3) Share with any	**(4) Spending in $**
Free Care	0.931	2166.1	0.932	2173.9
	(0.006)	(78.76)	(0.006)	(72.06)
25% Coinsurance	0.853	1535.9	0.852	1580.1
	(0.013)	(130.5)	(0.012)	(115.2)
50% Coinsurance	0.832	1590.7	0.826	1634.1
	(0.018)	(273.7)	(0.016)	(279.6)
95% Coinsurance	0.808	1691.6	0.810	1639.2
	(0.011)	(95.40)	(0.009)	(88.48)
family x month x site fixed effects	X	X	X	X
covariates			X	X
N	14777	14777	14777	14777

Assumptions

1. **Model**: The optimal insurance model as presented before
2. **Prior**: Gaussian process prior for *m*, squared exponential in distance, uninformative about level and slope
3. **Relative value** of funds for sick people vs contributors: $\lambda = 1.5$
4. Pooling data: across levels of maximum dollar expenditure

Under these assumptions we find:

Optimal copay equals 18%
(But free care is almost as good)


2000
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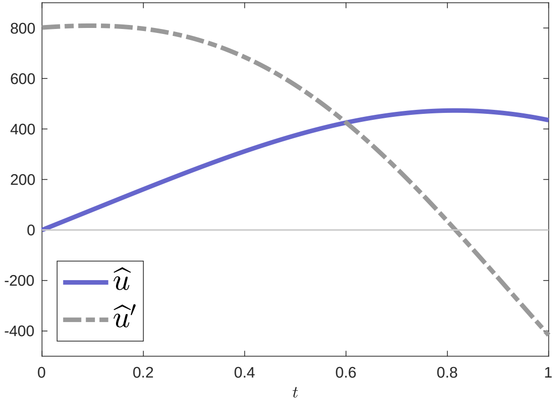
800
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200
0
-200
-400
0
0.2
0.4
0.6
0.8
1
t
$\widehat{u}$
$\widehat{u}'$

References

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- Envelope theorem:

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- Application to optimal insurance and taxation:

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