

A Ride in Targeted Learning Territory

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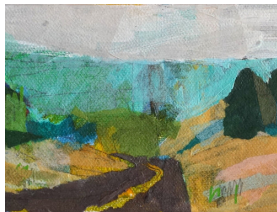
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Long Mendocino Drive
(detail, Liana Steinmetz)

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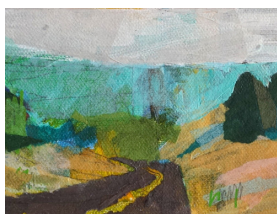
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Welcome



This is either the website or the text called “**A Ride in Targeted Learning Territory**”. In the former case, the text can be downloaded by clicking on the dedicated button in the top part of the webpage. In the latter case, the website can be browsed at <https://achambaz.github.io/tlride/>.



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Organization

The text takes the form of a series of brief sections. The main sections combine theoretical and computational developments. The code is written in the programming language R [R Core Team, 2019]. R is widely used among statisticians and data scientists to develop statistical software and data analysis.

Regularly, a section is inserted that proposes exercises. Each such section is indicated by the  symbol. The symbol  also indicates those sections of which the content is more involved.

Overview

After a short introduction, we present the reproducible experiment that will play a central role throughout the text. Then, we introduce the main parameter of interest. We comment upon some of its properties that are useful from a statistical perspective. This paves the way to the presentation of several estimators that are increasingly more powerful statistically. The discussion takes us into *targeted learning territory*.

Audience

The text might be of interest to students in statistics and machine learning. It might also serve as a gentle introduction to targeted learning in both its theoretical and computational

aspects before delving deeper into the literature [van der Laan and Rose, 2011], [van der Laan and Rose, 2018].

The text was presented at the Journées d'Étude en Statistique 2018 held in Fréjus (France) in October 2018 and at the First Summer School in Statistics and Data Science for Young Researchers from French-speaking Africa held at AIMS Senegal (MBour, Senegal) in July 2019.

Technical details

The text is written in RMarkdown with bookdown. Assuming that the `knitr` package is installed, you can retrieve all the R code by cloning this [github](#) repository then running

```
knitr::purl("abcd.Rmd")
```

Part I

On the road

Section 1

A ride

1.1 Introduction

Our ambition is to present a gentle introduction to the field of targeted learning. As an example, we consider statistical inference on a simple causal quantity that is ubiquitous in the causal literature. We use this exemplar parameter to introduce key concepts that can be applied to more complicated problems. The introduction weaves together two main threads, one theoretical and the other computational.

1.1.1 A causal story

We focus on a causal story where a random reward (a real number between 0 and 1) is given based on an action undertaken (one among two) and the random context where the action is performed (summarized by a real number between 0 and 1). The causal quantity of interest is the average difference of the two counterfactual rewards. This is a story as old as time. Should we take the red pill or the blue pill? Should we show our customers advertisement A or advertisement B? Should we require individuals to undergo cancer screening? At their core, each of these questions is asking what action should be taken to maximize a “reward.”

We will build several estimators and discuss their respective merits, theoretically and computationally. The construction of the most involved estimator will unfold in *targeted learning territory*, at the frontier of machine learning and semiparametrics, the statistical theory of inference based on semiparametric models.

1.1.2 The `tlrider` package

The computational illustrations will be developed based on the companion package `tlrider`. The package can be installed by running the following code:

```
devtools::install_github("achambaz/tlride/tlrider")
```

The version used in this document is 1.1.0.

Additional packages are also required, including `tidyverse` [Wickham and Grolemund, 2016], `caret` [Kuhn, 2020] and `ggdag` [Barrett, 2018]. Assuming that these are installed too, we can run the next chunk of code:

```
set.seed(3141516) ## because reproducibility matters...  
library(tidyverse)  
library(caret)  
library(ggdag)  
library(tlrider)
```

1.1.3 What we will discuss

To begin, we discuss the nature of the parameter of interest, viewing it as the value of a statistical mapping evaluated at the law of the data (Section 2), with an emphasis on the smoothness and double-robustness properties inherited from the mapping (Sections 3 and 4). We then turn to the estimation of the parameter of interest. We first introduce and comment upon a simple inference strategy assuming provisionally that a relevant feature of the law of the data is known to us (Section 6). Second, we present the notion of nuisance parameters and adopt an algorithmic stance on their estimation (Section 7). Third, we introduce and comment upon two “naive” inference strategies (Section 8), the one-step correction procedure (Section 9) and, finally, the targeted minimum loss estimation procedure tailored to the inference of the parameter of main interest. In the appendix, we collect our notation (Section A), and present some results that are used in the main text and their proofs (Sections B and C).

1.2 A simulation study

1.2.1 Reproducible experiment as a law

We are interested in a reproducible experiment. Every time this experiment is run, it generates an observation that we call O . We view O as a random variable drawn from *the law of the experiment* that we denote by P_0 .

We view P_0 as an element of *the model* \mathcal{M} . The model is a collection of laws. In particular, the model contains all laws that we think may plausibly describe the law of the experiment. Thus, the choice of model is based on our scientific knowledge of the experiment. The more we know about the experiment, the smaller is \mathcal{M} . In all our examples, we use large models that reflect a lack of knowledge about many aspects of the experiment.

1.2.2 A synthetic reproducible experiment

Instead of considering a real-life reproducible experiment, we focus for pedagogical purposes on a *synthetic* reproducible experiment. Thus we can from now on take on two different roles: that of an *oracle* knowing completely the nature of the experiment, and that of a *statistician* eager to know more about the experiment by observing some of its outputs.

Let us run the example built into the `tlrider` package:

```
example(tlrider)
```

A few objects have been defined:

```
ls()
#> [1] "another_experiment" "experiment"          "expit"
#> [4] "filter"             "logit"               "sigma0"
```

The function `expit` implements the link function $\text{expit} : \mathbb{R} \rightarrow]0, 1[$ given by $\text{expit}(x) \doteq (1 + e^{-x})^{-1}$. The function `logit` implements its inverse function $\text{logit} :]0, 1[\rightarrow \mathbb{R}$ given by $\text{logit}(p) \doteq \log[p/(1 - p)]$.

Let us take a look at `experiment`:

```
experiment
#> A law for (W,A,Y) in [0,1] x {0,1} x [0,1].
#>
#> If the law is fully characterized, you can use method
#> 'sample_from' to sample from it.
#>
#> If you built the law, or if you are an _oracle_, you can also
#> use methods 'reveal' to reveal its relevant features (QW, Gbar,
#> Qbar, qY -- see '?reveal'), and 'alter' to change some of them.
#>
#> If all its relevant features are characterized, you can use
#> methods 'evaluate_psi' to obtain the value of 'Psi' at this law
#> (see '?evaluate_psi') and 'evaluate_eic' to obtain the efficient
#> influence curve of 'Psi' at this law (see '?evaluate_eic').
```

The law P_0 of the synthetic experiment `experiment` built by us generates a generic observation O that decomposes as

$$O \doteq (W, A, Y) \in [0, 1] \times \{0, 1\} \times [0, 1].$$

We interpret W as a real valued summary measure of a random context where an action A chosen among two is undertaken, leading to a real valued reward Y .

We can sample from the experiment (simply run `?sample_from` to see the man page of

method `sample_from`). The next chunk of code runs the experiment five times, independently:

```
(five_obs <- sample_from(experiment, n = 5))
#>           W A      Y
#> [1,] 0.414 1 0.996
#> [2,] 0.409 1 0.669
#> [3,] 0.404 0 0.825
#> [4,] 0.462 1 0.539
#> [5,] 0.404 1 0.986
```

1.2.3 Revealing experiment

Acting as oracles, we can peek into `experiment` and *reveal* a selection of relevant features (simply run `?reveal` to see the man page of method `reveal`). Made by us, the selection exhibits features that will play an important role in the text.

```
relevant_features <- reveal(experiment)
names(relevant_features)
#> [1] "QW"           "Gbar"          "Qbar"          "qY"           "sample_from"
```

We have an oracular knowledge of `experiment` and can thus comment upon the features of P_0 revealed in `relevant_features`.

QW

The QW feature describes the marginal law of W , that we call $Q_{0,W}$.¹

```
relevant_features$QW
#> function(W,
#>           mixture_weights = c(1/10, 9/10, 0),
#>           mins = c(0, 11/30, 0),
#>           maxs = c(1, 14/30, 1)) {
#>   out <- sapply(1:length(mixture_weights),
#>               function(ii){
#>                 mixture_weights[ii] *
#>                 stats::dunif(W,
#>                               min = mins[ii],
#>                               max = maxs[ii])
#>               })
#>   return(rowSums(out))
#> }
```

¹A summary of the notation used throughout the text is presented there, in Appendix A.


```
#>      }
#> <environment: 0xf3ca190>
```

It appears that $Q_{0,W}$ is a mixture of the uniform laws over $[0, 1]$ (weight $1/10$) and $[11/30, 14/30]$ (weight $9/10$).²

Gbar

The **Gbar** feature describes the conditional probability of action $A = 1$ given W . For each $a \in \{0, 1\}$, we denote

$$\begin{aligned}\bar{G}_0(W) &\doteq \Pr_{P_0}(A = 1|W), \\ \ell\bar{G}_0(a, W) &\doteq \Pr_{P_0}(A = a|W).\end{aligned}$$

Obviously,

$$\ell\bar{G}_0(A, W) \doteq A\bar{G}_0(W) + (1 - A)(1 - \bar{G}_0(W)).$$

```
relevant_features$Gbar
#> function(W) {
#>      expit(1 + 2 * W - 4 * sqrt(abs((W - 5/12))))
#>      }
#> <environment: 0xf3ca190>
```

Note how real numbers of the form $1 + 2W - 4\sqrt{|W - 5/12|}$ are mapped into the interval $[0, 1]$ by the expit link function. We refer the reader to Figure 7.2 for a visualization of \bar{G}_0 .

qY

The **qY** feature describes the conditional density of Y given A and W . For each $y \in]0, 1[$, we denote by $q_{0,Y}(y, A, W)$ the conditional density evaluated at y of Y given A and W .

```
relevant_features$qY
#> function(obs, Qbar, shape10 = 2, shape11 = 3){
#>      A <- obs[, "A"]
#>      AW <- obs[, c("A", "W")]
#>      QAW <- Qbar(AW)
#>      shape1 <- ifelse(A == 0, shape10, shape11)
#>      stats::dbeta(Y,
#>                    shape1 = shape1,
#>                    shape2 = shape1 * (1 - QAW) / QAW)
#>      }
#> <environment: 0xf3ca190>
```

²We fine-tuned the marginal law $Q_{0,W}$ of W to make it easier later on to drive home important messages.

It appears that the conditional law of Y given A and W is the Beta law with conditional mean and variance characterized by the `Qbar` feature of `experiment` (see below) and the `shape10` and `shape11` parameters.

Qbar

As for the `Qbar` feature, it describes the conditional mean of Y given A and W .

```
relevant_features$Qbar
#> function(AW) {
#>     A <- AW[, "A"]
#>     W <- AW[, "W"]
#>     A * (cos((-1/2 + W) * pi) * 2/5 + 1/5 +
#>         (1/3 <= W & W <= 1/2) / 5 +
#>         (W >= 3/4) * (W - 3/4) * 2) +
#>     (1 - A) * (sin(4 * W^2 * pi) / 4 + 1/2)
#> }
#> <bytecode: 0x104fa668>
#> <environment: 0xf3ca190>
```

We denote $\bar{Q}_0(A, W) = E_{P_0}(Y|A, W)$ the conditional mean of Y given A and W . Note how $\bar{Q}_0(A, W)$ does depend heavily on A and W . We refer the reader to Section 1.3 for a visualization of \bar{Q}_0 .

sample_from

Finally, the `sample_from` feature is the function called by method `sample_from` when it is applied to an object of class `LAW`, like `experiment`.

```
relevant_features$sample_from
#> function(n, ideal = FALSE) {
#>     ## preliminary
#>     n <- R.utils::Arguments$getInteger(n, c(1, Inf))
#>     ideal <- R.utils::Arguments$getLogical(ideal)
#>     ## ## 'Gbar' and 'Qbar' factors
#>     Gbar <- experiment$.Gbar
#>     Qbar <- experiment$.Qbar
#>     ## sampling
#>     ## ## context
#>     params <- formals(experiment$.QW)
#>     mixture_weights <- eval(params$mixture_weights)
#>     mins <- eval(params$mins)
#>     maxs <- eval(params$maxs)
```

```

#>      W <- sample_from_mixture_of_uniforms(n, mixture_weights,
#>                                           mins, maxs)
#>      ## ## counterfactual rewards
#>      zeroW <- cbind(A = 0, W)
#>      oneW <- cbind(A = 1, W)
#>      Qbar_zeroW <- Qbar(zeroW)
#>      Qbar_oneW <- Qbar(oneW)
#>      Yzero <- stats::rbeta(n,
#>                           shape1 = 2,
#>                           shape2 = 2 * (1 - Qbar_zeroW) / Qbar_zeroW)
#>      Yone <- stats::rbeta(n,
#>                          shape1 = 3,
#>                          shape2 = 3 * (1 - Qbar_oneW) / Qbar_oneW)
#>      ## ## action undertaken
#>      A <- stats::rbinom(n, size = 1, prob = Gbar(W))
#>      ## ## actual reward
#>      Y <- A * Yone + (1 - A) * Yzero
#>      ## ## observation
#>      if (ideal) {
#>        obs <- cbind(W = W, Yzero = Yzero, Yone = Yone, A = A, Y = Y)
#>      } else {
#>        obs <- cbind(W = W, A = A, Y = Y)
#>      }
#>      return(obs)
#>    }
#> <bytecode: 0xedf6bc0>
#> <environment: 0xf3ca190>

```

We will comment upon the `ideal` argument in the above `sample_from` feature in Section 2.1.

1.3 Visualization

1. Run the following chunk of code. It visualizes the conditional mean \bar{Q}_0 .

```

Gbar <- relevant_features$Gbar
Qbar <- relevant_features$Qbar
QW <- relevant_features$QW

features <- tibble(w = seq(0, 1, length.out = 1e3)) %>%
  mutate(Qw = QW(w),
         Gw = Gbar(w),

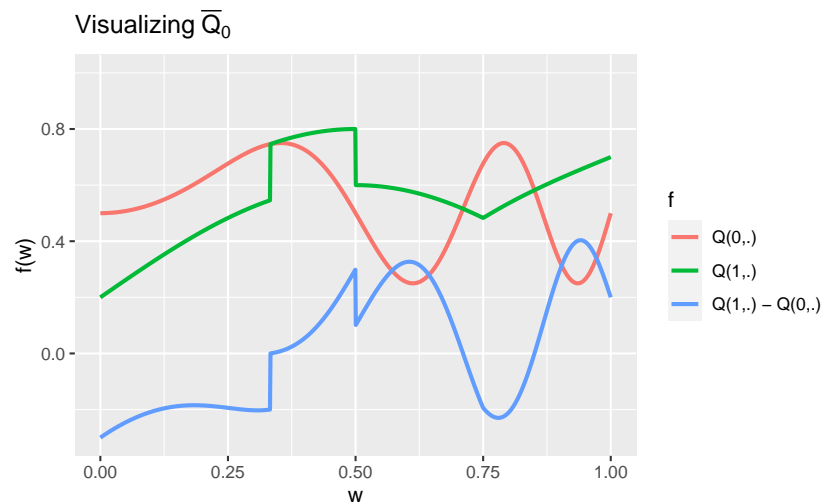
```

```

Q1w = Qbar(cbind(A = 1, W = w)),
Q0w = Qbar(cbind(A = 0, W = w)),
blip_Qw = Q1w - Q0w)

features %>% select(-Qw, -Gw) %>%
  rename("Q(1,.)" = Q1w,
         "Q(0,.)" = Q0w,
         "Q(1,.) - Q(0,.)" = blip_Qw) %>%
  pivot_longer(-w, names_to = "f", values_to = "value") %>%
  ggplot() +
  geom_line(aes(x = w, y = value, color = f), size = 1) +
  labs(y = "f(w)", title = bquote("Visualizing" ~ bar(Q)[0])) +
  ylim(NA, 1)

```



2. Adapt the above chunk of code to visualize the marginal density $Q_{0,W}$ and conditional probability \bar{G}_0 .

1.4 🌀 Make your own experiment

You can easily make your own experiment.

1. Check out the man page of method `alter` by running `?alter`.
2. Run the following chunk of code:

```

my_experiment <- LAW() ## creates an object of class 'LAW'
alter(my_experiment, ## characterize its relevant features
      QW = function(W) {
        out <- rep_len(0, length(W))

```

```

    out[W == 0] <- 1/4
    out[W == 1] <- 3/4
    return(out)
  },
  Gbar = function(W) {
    out <- rep_len(0, length(W))
    out[W == 0] <- 1/3
    out[W == 1] <- 3/5
    return(out)
  },
  Qbar = function(AW) {
    probs <- matrix(c(1/2, 2/3, 7/8, 4/5), ncol = 2,
                     dimnames = list(c("A=0", "A=1"),
                                     c("W=0", "W=1")))
    probs[cbind(AW[, "A"] + 1, AW[, "W"] + 1)]
  },
  qY = function(obs) {
    probs <- matrix(c(1/2, 2/3, 7/8, 4/5), ncol = 2,
                     dimnames = list(c("A=0", "A=1"),
                                     c("W=0", "W=1")))
    probs <- probs[cbind(obs[, "A"] + 1, obs[, "W"] + 1)]
    obs[, "Y"] * probs + (1 - obs[, "Y"]) * (1 - probs)
  },
  sample_from = function(n) {
    ## preliminary
    n <- R.utils::Arguments$getInteger(n, c(1, Inf))
    ## 'QW', 'Gbar' and 'Qbar' features
    QW <- my_experiment$.QW
    Gbar <- my_experiment$.Gbar
    Qbar <- my_experiment$.Qbar
    ## sampling
    W <- rbinom(n, size = 1, prob = QW(1))
    A <- rbinom(n, size = 1, prob = Gbar(W))
    AW <- cbind(W = W, A = A)
    Y <- rbinom(n, size = 1, Qbar(AW))
    return(cbind(AW, Y = Y))
  })

```

3. What does the next chunk do?

```

(sample_from(my_experiment, 3))
#>      W A Y
#> [1,] 1 0 1

```

```
#> [2,] 0 0 1
#> [3,] 1 1 1
```

4. Characterize entirely the law of my_experiment. Hint:

```
obs <- sample_from(my_experiment, 1e4)
obs %>% as_tibble %>% group_by(W, A, Y) %>%
  summarize(how_many = n()) %>% ungroup
#> # A tibble: 8 x 4
#>       W     A     Y how_many
#>   <int> <int> <int>   <int>
#> 1     0     0     0     826
#> 2     0     0     1     833
#> 3     0     1     0     286
#> 4     0     1     1     561
#> 5     1     0     0     376
#> 6     1     0     1    2564
#> # ... with 2 more rows
obs %>% as_tibble %>% group_by(W, A) %>%
  summarize(prob = mean(Y)) %>% ungroup
#> # A tibble: 4 x 3
#>       W     A prob
#>   <int> <int> <dbl>
#> 1     0     0 0.502
#> 2     0     1 0.662
#> 3     1     0 0.872
#> 4     1     1 0.798
```

5. Now, make your own experiment.

Section 2

The parameter of interest

2.1 The parameter of interest

2.1.1 Definition

It happens that we especially care for a finite-dimensional feature of P_0 that we denote by ψ_0 . Its definition involves two of the aforementioned infinite-dimensional features, the marginal law $Q_{0,W}$ of W and the conditional mean \bar{Q}_0 of Y given A and W :

$$\begin{aligned}\psi_0 &\doteq \int (\bar{Q}_0(1, w) - \bar{Q}_0(0, w)) dQ_{0,W}(w) \\ &= E_{P_0} (E_{P_0}(Y \mid A = 1, W) - E_{P_0}(Y \mid A = 0, W)).\end{aligned}\tag{2.1}$$

Acting as oracles, we can compute explicitly the numerical value of ψ_0 . The `evaluate_psi` method makes it very easy (simply run `?estimate_psi` to see the man page of the method):

```
(psi_zero <- evaluate_psi(experiment))  
#> [1] 0.0832
```

2.1.2 A causal interpretation

Our interest in ψ_0 is of causal nature. Taking a closer look at the `sample_from` feature of `experiment` reveals indeed that the random making of an observation O drawn from P_0 can be summarized by the following directed acyclic graph:

```
dagify(  
  Y ~ A + Y1 + Y0, A ~ W, Y1 ~ W, Y0 ~ W,  
  labels = c(Y = "Actual reward",  
             A = "Action",
```

```

Y1 = "Counterfactual reward\n of action 1",
Y0 = "Counterfactual reward\n of action 0",
W = "Context of action"),
coords = list(
  x = c(W = 0, A = -1, Y1 = 1.5, Y0 = 0.25, Y = 1),
  y = c(W = 0, A = -1, Y1 = -0.5, Y0 = -0.5, Y = -1)),
outcome = "Y",
exposure = "A",
latent = c("Y0", "Y1")) %>% tidy_dagitty %>%
ggdag(text = TRUE, use_labels = "label") + theme_dag_grey()

```

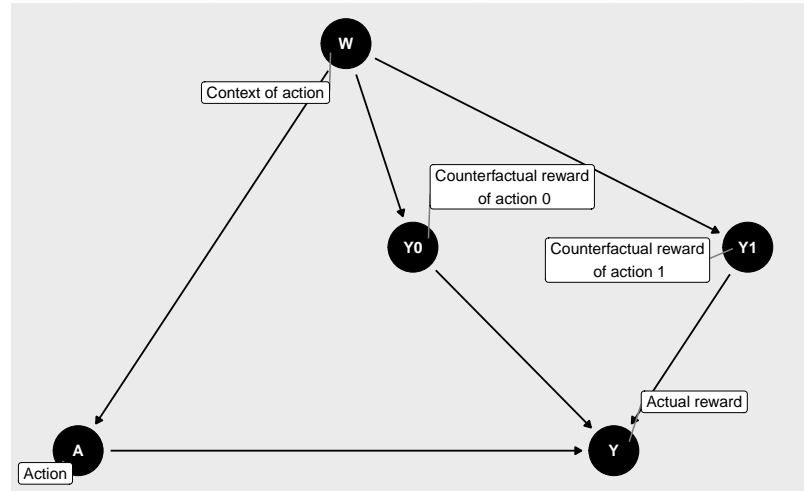


Figure 2.1: Directed acyclic graph summarizing the inner causal mechanism at play in experiment.

In words, the experiment unfolds like this (see also Section B.1):

1. a context of action $W \in [0, 1]$ is randomly generated;
2. two counterfactual rewards $Y_0 \in [0, 1]$ and $Y_1 \in [0, 1]$ are generated conditionally on W ;
3. an action $A \in \{0, 1\}$ (among two possible actions called $a = 0$ and $a = 1$) is undertaken, *(i)* knowing the context but *not* the counterfactual rewards, and *(ii)* in such a way that both actions can always be considered;
4. the action yields a reward Y , which equals either Y_0 or Y_1 depending on whether action $a = 0$ or $a = 1$ has been undertaken;
5. summarize the course of the experiment with $O \doteq (W, A, Y)$, thus concealing Y_0 and Y_1 .

The above description of the experiment is useful to reinforce what it means to run the “ideal” experiment by setting argument `ideal` to `TRUE` in a call to `sample_from` for `experiment` (see Section 2.1.3). Doing so triggers a modification of the nature of the experiment, enforcing that the counterfactual rewards Y_0 and Y_1 be part of the summary of the experiment eventually. In light of the above enumeration,

$$\mathbb{O} \doteq (W, Y_0, Y_1, A, Y)$$

is output, as opposed to its summary measure O . This defines another experiment and its law, that we denote \mathbb{P}_0 .

It is straightforward to show that

$$\begin{aligned}\psi_0 &= E_{\mathbb{P}_0}(Y_1 - Y_0) \\ &= E_{\mathbb{P}_0}(Y_1) - E_{\mathbb{P}_0}(Y_0).\end{aligned}\tag{2.2}$$

Thus, ψ_0 describes the average difference of the two counterfactual rewards. In other words, ψ_0 quantifies the difference in average of the reward one would get in a world where one would always enforce action $a = 1$ with the reward one would get in a world where one would always enforce action $a = 0$. This said, it is worth emphasizing that ψ_0 is a well-defined parameter beyond its causal interpretation, and that it describes a standardized association between the action A and reward Y .

2.1.3 A causal computation

We can use our position as oracles to sample observations from the ideal experiment. We call `sample_from` for `experiment` with its argument `ideal` set to `TRUE` in order to numerically approximate ψ_0 . By the law of large numbers, the following code approximates ψ_0 and shows its approximate value.

```
B <- 1e6
ideal_obs <- sample_from(experiment, B, ideal = TRUE)
(psi_approx <- mean(ideal_obs[, "Yone"] - ideal_obs[, "Yzero"]))
#> [1] 0.083
```

The object `psi_approx` contains an approximation to ψ_0 based on `B` observations from the ideal experiment. The random sampling of observations results in uncertainty in the numerical approximation of ψ_0 . This uncertainty can be quantified by constructing a 95% confidence interval for ψ_0 . The central limit theorem and Slutsky’s lemma allow us to build such an interval as follows.

```
sd_approx <- sd(ideal_obs[, "Yone"] - ideal_obs[, "Yzero"])
alpha <- 0.05
```

```
(psi_approx_CI <- psi_approx + c(-1, 1) *
  qnorm(1 - alpha / 2) * sd_approx / sqrt(B))
#> [1] 0.0824 0.0836
```

We note that the interpretation of this confidence interval is that in 95% of draws of size B from the ideal data generating experiment, the true value of ψ_0 will be contained in the generated confidence interval.

2.2 An alternative parameter of interest

Equality (2.2) shows that parameter ψ_0 (2.1) is the difference in average rewards if we enforce action $a = 1$ rather than $a = 0$. An alternative way to describe the rewards under different actions involves *quantiles* as opposed to *averages*.

Let

$$Q_{0,Y}(y, A, W) \doteq \int_0^y q_{0,Y}(u, A, W) du$$

be the conditional cumulative distribution of reward Y given A and W , evaluated at $y \in]0, 1[$, that is implied by P_0 . For each action $a \in \{0, 1\}$ and $c \in]0, 1[$, introduce

$$\gamma_{0,a,c} \doteq \inf \left\{ y \in]0, 1[: \int Q_{0,Y}(y, a, w) dQ_{0,W}(w) \geq c \right\}. \quad (2.3)$$

(Note: \inf merely generalizes \min , accounting for the fact that the minimum may fail to be achieved.)

It is not very difficult to check (see Problem 1 below) that

$$\gamma_{0,a,c} = \inf \left\{ y \in]0, 1[: \Pr_{\mathbb{P}_0}(Y_a \leq y) \geq c \right\}. \quad (2.4)$$

Thus, $\gamma_{0,a,c}$ can be interpreted as a covariate-adjusted c -th quantile reward when action a is enforced. The difference

$$\delta_{0,c} \doteq \gamma_{0,1,c} - \gamma_{0,0,c} \quad (2.5)$$

is the c -th quantile counterpart to parameter ψ_0 (2.1).

1. \geq Prove (2.4).
2. \geq Compute the numerical value of $\gamma_{0,a,c}$ for each $(a, c) \in \{0, 1\} \times \{1/4, 1/2, 3/4\}$ using the appropriate features of **experiment** (see **relevant_features**). Based on these results, report the numerical value of $\delta_{0,c}$ for each $c \in \{1/4, 1/2, 3/4\}$.
3. Approximate the numerical values of $\gamma_{0,a,c}$ for each $(a, c) \in \{0, 1\} \times \{1/4, 1/2, 3/4\}$ by drawing a large sample from the “ideal” data experiment and using empirical quantile estimates. Deduce from these results a numerical approximation to $\delta_{0,c}$ for $c \in \{1/4, 1/2, 3/4\}$. Confirm that your results closely match those obtained in the previous problem.

2.3 The statistical mapping of interest

The noble way to define a statistical parameter is to view it as the value of a statistical mapping at the law of the experiment of interest. Beyond the elegance, this has paramount statistical implications.

2.3.1 Opening discussion

Oftentimes, the premise of a statistical analysis is presented like this. One assumes that the law P_0 of the experiment of interest belongs to a statistical model

$$\{P_\theta : \theta \in T\}.$$

The statistical model is identifiable, meaning that if two elements P_θ and $P_{\theta'}$ coincide, then necessarily $\theta = \theta'$. Therefore, there exists a unique $\theta_0 \in T$ such that $P_0 = P_{\theta_0}$, and one wishes to estimate θ_0 .

For instance, each P_θ could be the Gaussian law with mean $\theta \in T \doteq \mathbb{R}$ and variance 1, and one could wish to estimate the mean θ_0 of P_0 . To do so, one could rely on n observations X_1, \dots, X_n drawn independently from P_0 . The empirical mean

$$\theta_n \doteq \frac{1}{n} \sum_{i=1}^n X_i$$

estimates θ_0 . If we assume that $\text{Var}_{P_0}(X_1)$ is finite, then θ_n satisfies many useful properties. In particular, it can be used to construct confidence intervals.

Of course, the mean of a law is defined beyond the small model $\{P_\theta : \theta \in \mathbb{R}\}$. Let \mathcal{M} be the set of laws P on \mathbb{R} such that $\text{Var}_P(X)$ is finite. In particular, $P_0 \in \mathcal{M}$. For every $P \in \mathcal{M}$, the mean $E_P(X)$ is well defined. Thus, we can introduce the *statistical mapping* $\Theta : \mathcal{M} \rightarrow \mathbb{R}$ given by

$$\Theta(P) \doteq E_P(X).$$

Interestingly, the empirical measure P_n ¹ is an element of \mathcal{M} . Therefore, the statistical mapping Θ can be evaluated at P_n :

$$\Theta(P_n) = \frac{1}{n} \sum_{i=1}^n X_i = \theta_n.$$

We *recover* the empirical mean, and understand that it is a *substitution* estimator of the mean: in order to estimate $\Theta(P_0)$, we *substitute* P_n for P_0 within Θ .²

¹The empirical measure P_n is the law such that (i) X drawn from P_n takes its values in $\{X_1, \dots, X_n\}$, and (ii) $X = X_i$ with probability n^{-1}

²There are many interesting parameters Θ for which $\Theta(P_n)$ is not defined, see for instance (2.6), our parameter of main interest.

Substitution-based estimators are particularly valuable notably because they, by construction, satisfy all the constraints to which the targeted parameter is subjected. Some of the estimators that we will build together are substitution-based, some are not.

2.3.2 The parameter as the value of a statistical mapping at the experiment

We now go back to our main topic of interest. Suppose we know beforehand that O drawn from P_0 takes its values in $\mathcal{O} \doteq [0, 1] \times \{0, 1\} \times [0, 1]$ and that $\bar{G}_0(W) \doteq \Pr_{P_0}(A = 1|W)$ is bounded away from zero and one $Q_{0,W}$ -almost surely (this is the case indeed). Then we can define model \mathcal{M} as the set of all laws P on \mathcal{O} such that

$$\bar{G}(W) \doteq \Pr_P(A = 1|W)$$

is bounded away from zero and one Q_W -almost surely, where Q_W is the marginal law of W under P .

Let us also define generically \bar{Q} as

$$\bar{Q}(A, W) \doteq \mathbb{E}_P(Y|A, W).$$

Note how we have suppressed the dependence of \bar{G} and \bar{Q} on P for notational simplicity.

Central to our approach is viewing ψ_0 as the value at P_0 of the statistical mapping Ψ from \mathcal{M} to $[0, 1]$ characterized by

$$\begin{aligned} \Psi(P) &\doteq \int (\bar{Q}_P(1, w) - \bar{Q}_P(0, w)) dQ_W(w) \\ &= \mathbb{E}_P(\bar{Q}_P(1, W) - \bar{Q}_P(0, W)), \end{aligned} \tag{2.6}$$

a clear extension of (2.1) where, for once, we make the dependence of \bar{Q} on P explicit to emphasize how $\Psi(P)$ truly depends on P .

2.3.3 The value of the statistical mapping at another experiment

When we ran `example(tlrider)` earlier, we created an object called `another_experiment`:

```
another_experiment
#> A law for (W,A,Y) in [0,1] x {0,1} x [0,1].
#>
#> If the law is fully characterized, you can use method
#> 'sample_from' to sample from it.
#>
#> If you built the law, or if you are an _oracle_, you can also
#> use methods 'reveal' to reveal its relevant features (QW, Gbar,
```

```

#> Qbar, qY -- see '?reveal'), and 'alter' to change some of them.
#>
#> If all its relevant features are characterized, you can use
#> methods 'evaluate_psi' to obtain the value of 'Psi' at this law
#> (see '?evaluate_psi') and 'evaluate_eic' to obtain the efficient
#> influence curve of 'Psi' at this law (see '?evaluate_eic').
reveal(another_experiment)
#> $QW
#> function(x, min = 1/10, max = 9/10){
#>     stats::dunif(x, min = min, max = max)
#> }
#> <environment: 0x10837e90>
#>
#> $Gbar
#> function(W) {
#>     sin((1 + W) * pi / 6)
#> }
#> <environment: 0x10837e90>
#>
#> $Qbar
#> function(AW, h) {
#>     A <- AW[, "A"]
#>     W <- AW[, "W"]
#>     expit( logit( A * W + (1 - A) * W^2 ) +
#>           h * 10 * sqrt(W) * A )
#> }
#> <environment: 0x10837e90>
#>
#> $qY
#> function(obs, Qbar, shape1 = 4){
#>     AW <- obs[, c("A", "W")]
#>     QAW <- Qbar(AW)
#>     stats::gdbeta(Y,
#>                   shape1 = shape1,
#>                   shape2 = shape1 * (1 - QAW) / QAW)
#> }
#> <environment: 0x10837e90>
#>
#> $sample_from
#> function(n, h) {
#>     ## preliminary
#>     n <- R.utils::Arguments$getInteger(n, c(1, Inf))

```

```

#>      h <- R.utils::Arguments$getNumeric(h)
#>      ## ## 'Gbar' and 'Qbar' factors
#>      Gbar <- another_experiment$.Gbar
#>      Qbar <- another_experiment$.Qbar
#>      ## sampling
#>      ## ## context
#>      params <- formals(another_experiment$.QW)
#>      W <- stats::runif(n, min = eval(params$min),
#>                        max = eval(params$max))
#>      ## ## action undertaken
#>      A <- stats::rbinom(n, size = 1, prob = Gbar(W))
#>      ## ## reward
#>      params <- formals(another_experiment$.qY)
#>      shape1 <- eval(params$shape1)
#>      QAW <- Qbar(cbind(A = A, W = W), h = h)
#>      Y <- stats::rbeta(n,
#>                        shape1 = shape1,
#>                        shape2 = shape1 * (1 - QAW) / QAW)
#>      ## ## observation
#>      obs <- cbind(W = W, A = A, Y = Y)
#>      return(obs)
#>    }
#> <environment: 0x10837e90>
(two_obs_another_experiment <- sample_from(another_experiment, 2, h = 0))
#>      W A      Y
#> [1,] 0.101 0 0.00841
#> [2,] 0.620 1 0.51166

```

By taking an oracular look at the output of `reveal(another_experiment)`, we discover that the law $\Pi_0 \in \mathcal{M}$ encoded by default (*i.e.*, with $h=0$) in `another_experiment` differs starkly from P_0 .

However, the parameter $\Psi(\Pi_0)$ is well defined. Straightforward algebra shows that $\Psi(\Pi_0) = 59/300$. The numeric computation below confirms the equality.

```

(psi_Pi_zero <- evaluate_psi(another_experiment, h = 0))
#> [1] 0.197
round(59/300, 3)
#> [1] 0.197

```

2.4 Alternative statistical mapping

We now resume the exercise of Section 2.2. Like we did in Section 2.3, we introduce a generic version of the relevant features $q_{0,Y}$ and $Q_{0,Y}$. Specifically, we define $q_Y(y, A, W)$ to be the conditional density of Y given A and W , evaluated at y , that is implied by a generic $P \in \mathcal{M}$. Similarly, we use Q_Y to denote the corresponding cumulative distribution function.

The covariate-adjusted c -th quantile reward for action $a \in \{0, 1\}$, $\gamma_{0,a,c}$ (2.3), may be viewed as the value at P_0 of a mapping $\Gamma_{a,c}$ from \mathcal{M} to $[0, 1]$ characterized by

$$\Gamma_{a,c}(P) = \inf \left\{ y \in]0, 1[: \int Q_Y(y, a, w) dQ_W(w) \geq c \right\}.$$

The difference in c -th quantile rewards, $\delta_{0,c}$ (2.5), may similarly be viewed as the value at P_0 of a mapping Δ_c from \mathcal{M} to $[0, 1]$, characterized by

$$\Delta_c(P) \doteq \Gamma_{1,c}(P) - \Gamma_{0,c}(P).$$

1. Compute the numerical value of $\Gamma_{a,c}(\Pi_0)$ for $(a, c) \in \{0, 1\} \times \{1/4, 1/2, 3/4\}$ using the relevant features of **another_experiment**. Based on these results, report the numerical value of $\Delta_c(\Pi_0)$ for each $c \in \{1/4, 1/2, 3/4\}$.
2. Approximate the value of $\Gamma_{0,a,c}(\Pi_0)$ for $(a, c) \in \{0, 1\} \times \{1/4, 1/2, 3/4\}$ by drawing a large sample from the “ideal” data experiment and using empirical quantile estimates. Deduce from these results a numerical approximation to $\Delta_{0,c}(\Pi_0)$ for each $c \in \{1/4, 1/2, 3/4\}$. Confirm that your results closely match those obtained in the previous problem.
3. Building upon the code you wrote to solve the previous problem, construct a confidence interval with asymptotic level 95% for $\Delta_{0,c}(\Pi_0)$, with $c \in \{1/4, 1/2, 3/4\}$.

2.5 Representations

In Section 2.3, we reoriented our view of the target parameter to be that of a statistical functional of the law of the observed data. Specifically, we viewed the parameter as a function of specific features of the observed data law, namely Q_W and \bar{Q} .

2.5.1 Yet another representation

It is straightforward to show an equivalent representation of the parameter as

$$\psi_0 = \int \frac{2a-1}{\ell \bar{G}_0(a, w)} y dP_0(w, a, y)$$

$$= E_{P_0} \left(\frac{2A - 1}{\ell \bar{G}_0(A, W)} Y \right). \quad (2.7)$$

Viewing again the parameter as a statistical mapping from \mathcal{M} to $[0, 1]$, it also holds that

$$\begin{aligned} \Psi(P) &= \int \frac{2a - 1}{\ell \bar{G}(a, w)} y dP(w, a, y) \\ &= E_P \left(\frac{2A - 1}{\ell \bar{G}_0(A, W)} Y \right). \end{aligned} \quad (2.8)$$

2.5.2 From representations to estimation strategies

Our reason for introducing this alternative view of the target parameter will become clear when we discuss estimation of the target parameter. Specifically, the representations (2.1) and (2.7) naturally suggest different estimation strategies for ψ_0 , as hinted in Section 2.3.1. The former suggests building an estimator of ψ_0 using estimators of \bar{Q}_0 and of $Q_{W,0}$. The latter suggests building an estimator of ψ_0 using estimators of $\ell \bar{G}_0$ and of P_0 .

We return to these ideas in later sections.

2.6 Alternative representation

1. \geq Show that for $a' = 0, 1$, $\gamma_{0,a',c}$ as defined in (2.3) can be equivalently expressed as

$$\inf \left\{ z \in]0, 1[: \int \frac{\mathbf{1}\{a = a'\}}{\ell \bar{G}(a', W)} \mathbf{1}\{y \leq z\} dP_0(w, a, y) \geq c \right\}.$$

Section 3

Smoothness

3.1 Fluctuating smoothly

Within our view of the target parameter as a statistical mapping evaluated at the law of the experiment, it is natural to inquire of properties this functional enjoys. For example, we may be interested in asking how the value of $\Psi(P)$ changes as we consider laws that *get nearer to P* in \mathcal{M} . If small deviations from P_0 result in large changes in $\Psi(P_0)$, then we might hypothesize that it will be difficult to produce stable estimators of ψ_0 . Fortunately, this turns out not to be the case for the mapping Ψ , and so we say that Ψ is a *smooth* statistical mapping.

To discuss how $\Psi(P)$ changes for distributions that *get nearer to P* in the model, we require a more concrete notion of *getting-nearness*. The notion hinges on fluctuations (or fluctuating models).

3.1.1 The `another_experiment` fluctuation

In Section 2.3.3, we discussed the nature of the object called `another_experiment` that was created when we ran `example(tlrider)`:

```
another_experiment
#> A law for (W,A,Y) in [0,1] x {0,1} x [0,1].
#>
#> If the law is fully characterized, you can use method
#> 'sample_from' to sample from it.
#>
#> If you built the law, or if you are an _oracle_, you can also
#> use methods 'reveal' to reveal its relevant features (QW, Gbar,
#> Qbar, qY -- see '?reveal'), and 'alter' to change some of them.
```

```

#>
#> If all its relevant features are characterized, you can use
#> methods 'evaluate_psi' to obtain the value of 'Psi' at this law
#> (see '?evaluate_psi') and 'evaluate_eic' to obtain the efficient
#> influence curve of 'Psi' at this law (see '?evaluate_eic').

```

The message is a little misleading. Indeed, `another_experiment` is not a law but, rather, a *collection* of laws indexed by a real-valued parameter `h`. This oracular statement (we built the object!) is evident when one looks again at the `sample_from` feature of `another_experiment`:

```

reveal(another_experiment)$sample_from
#> function(n, h) {
#>   ## preliminary
#>   n <- R.utils::Arguments$getInteger(n, c(1, Inf))
#>   h <- R.utils::Arguments$getNumeric(h)
#>   ## ## 'Gbar' and 'Qbar' factors
#>   Gbar <- another_experiment$.Gbar
#>   Qbar <- another_experiment$.Qbar
#>   ## sampling
#>   ## ## context
#>   params <- formals(another_experiment$.QW)
#>   W <- stats::runif(n, min = eval(params$min),
#>                     max = eval(params$max))
#>   ## ## action undertaken
#>   A <- stats::rbinom(n, size = 1, prob = Gbar(W))
#>   ## ## reward
#>   params <- formals(another_experiment$.qY)
#>   shape1 <- eval(params$shape1)
#>   QAW <- Qbar(cbind(A = A, W = W), h = h)
#>   Y <- stats::rbeta(n,
#>                     shape1 = shape1,
#>                     shape2 = shape1 * (1 - QAW) / QAW)
#>   ## ## observation
#>   obs <- cbind(W = W, A = A, Y = Y)
#>   return(obs)
#> }
#> <bytecode: 0xf3593b0>
#> <environment: 0x10837e90>

```

Let us call $\Pi_h \in \mathcal{M}$ the law encoded by `another_experiment` for a given `h` taken in $] -1, 1[$. Note that

$$\mathcal{P} \doteq \{\Pi_h : h \in] -1, 1[\}$$

defines a collection of laws, *i.e.*, a statistical model.

We say that \mathcal{P} is a *submodel* of \mathcal{M} because $\mathcal{P} \subset \mathcal{M}$. Moreover, we say that this submodel is *through* Π_0 since $\Pi_h = \Pi_0$ when $h = 0$. We also say that \mathcal{P} is a *fluctuation* of Π_0 .

One could enumerate many possible submodels in \mathcal{M} through Π_0 . It turns out that all that matters for our purposes is the form of the submodel in a neighborhood of Π_0 . We informally say that this local behavior describes the *direction* of a submodel through Π_0 . We formalize this notion Section 3.3.

We now have a notion of how to move through the model space $P \in \mathcal{M}$ and can study how the value of the parameter changes as we move away from a law P . Above, we said that Ψ is a smooth parameter if it does not change “too much” as we move towards P in any particular direction. That is, we should hope that Ψ is differentiable along our submodel at P .

This idea too is formalized in Section 3.3. We now turn to illustrating this idea numerically.

3.1.2 Numerical illustration

The code below evaluates how the parameter changes for laws in \mathcal{P} , and approximates the derivative of the parameter along the submodel \mathcal{P} at Π_0 . Recall that the numerical value of $\Psi(\Pi_0)$ has already been computed and is stored in object `psi_Pi_zero`.

```
approx <- seq(-1, 1, length.out = 1e2)
psi_Pi_h <- sapply(approx, function(t) {
  evaluate_psi(another_experiment, h = t)
})
slope_approx <- (psi_Pi_h - psi_Pi_zero) / approx
slope_approx <- slope_approx[which(approx > 0)]
ggplot() +
  geom_point(data = data.frame(x = approx, y = psi_Pi_h), aes(x, y),
    color = "#CC6666") +
  geom_segment(aes(x = -1, y = psi_Pi_zero - slope_approx,
    xend = 1, yend = psi_Pi_zero + slope_approx),
    arrow = arrow(length = unit(0.03, "npc")),
    color = "#9999CC") +
  geom_vline(xintercept = 0, color = "#66CC99") +
  geom_hline(yintercept = psi_Pi_zero, color = "#66CC99") +
  labs(x = "h", y = expression(Psi(Pi[h])))
```

The red curve represents the function $h \mapsto \Psi(\Pi_h)$. The blue line represents the tangent to the previous curve at $h = 0$, which indeed appears to be differentiable around $h = 0$. In Section 3.4, we derive a closed-form expression for the slope of the blue curve.

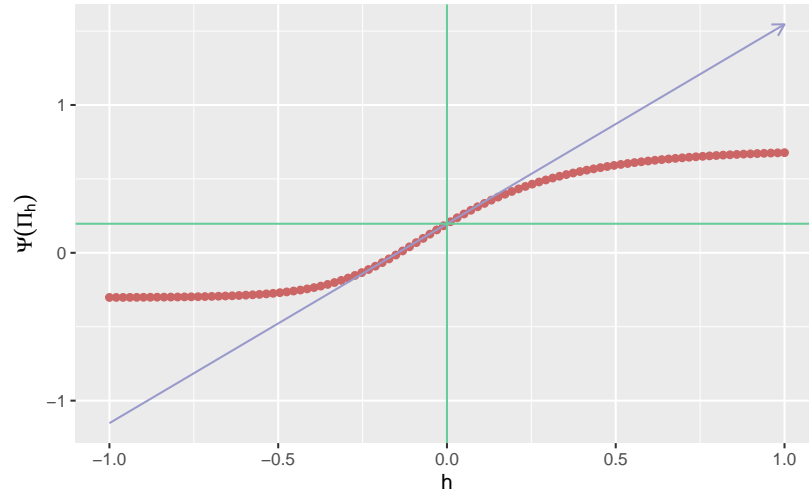


Figure 3.1: Evolution of statistical mapping Ψ along fluctuation $\{\Pi_h : h \in H\}$.

3.2 Yet another experiment

1. Adapt the code from Problem 1 in Section 1.3 to visualize $w \mapsto \mathbb{E}_{\Pi_h}(Y|A=1, W=w)$, $w \mapsto \mathbb{E}_{\Pi_h}(Y|A=0, W=w)$, and $w \mapsto \mathbb{E}_{\Pi_h}(Y|A=1, W=w) - \mathbb{E}_{\Pi_h}(Y|A=0, W=w)$, for $h \in \{-1/2, 0, 1/2\}$.
2. Run the following chunk of code.

```
yet_another_experiment <- copy(another_experiment)
alter(yet_another_experiment,
  Qbar = function(AW, h){
    A <- AW[, "A"]
    W <- AW[, "W"]
    expit( logit( A * W + (1 - A) * W^2 ) +
           h * (2*A - 1) / ifelse(A == 1,
                                   sin((1 + W) * pi / 6),
                                   1 - sin((1 + W) * pi / 6)) *
           (Y - A * W + (1 - A) * W^2))
  })
```

3. Justify that `yet_another_fluctuation` characterizes another fluctuation of Π_0 . Comment upon the similarities and differences between $\{\Pi_h : h \in]-1, 1[\}$ and $\{\Pi'_h : h \in]-1, 1[\}$.
4. Repeat Problem 1 above with Π'_h substituted for Π_h .
5. Re-produce Figure 3.1 for the $\{\Pi'_h : h \in]-1, 1[\}$ fluctuation. Comment on the similarities and differences between the resulting figure and Figure 3.1. In particular,

how does the behavior of the target parameter around $h = 0$ compare between laws Π_0 and Π'_0 ?

3.3 \supset More on fluctuations and smoothness

3.3.1 Fluctuations

Let us now formally define what it means for statistical mapping Ψ to be smooth at every $P \in \mathcal{M}$. Let H be the interval $] -1/M, M[$. For every $h \in H$, we can define a law $P_h \in \mathcal{M}$ by setting $P_h \ll P^1$ and

$$\frac{dP_h}{dP} \doteq 1 + hs, \quad (3.1)$$

where $s : \mathcal{O} \rightarrow \mathbb{R}$ is a (measurable) function of O such that $s(O)$ is not equal to zero P -almost surely, $E_P(s(O)) = 0$, and s bounded by M . We make the observation that

$$(i) \quad P_h|_{h=0} = P, \quad (ii) \quad \left. \frac{d}{dh} \log \frac{dP_h}{dP}(O) \right|_{h=0} = s(O). \quad (3.2)$$

Because of (i), $\{P_h : h \in H\}$ is a submodel through P , also referred to as a *fluctuation* of P . The fluctuation is a one-dimensional submodel of \mathcal{M} with univariate parameter $h \in H$. We note that (ii) indicates that the score of this submodel at $h = 0$ is s . Thus, we say that the fluctuation is *in the direction* of s .

Fluctuations of P do not necessarily take the same form as in (3.1). No matter how the fluctuation is built, for our purposes the most important feature of the fluctuation is its local shape in a neighborhood of P .

3.3.2 Smoothness and gradients

We are now prepared to provide a formal definition of smoothness of statistical mappings. We say that a statistical mapping Ψ is *smooth* at every $P \in \mathcal{M}$ if for each $P \in \mathcal{M}$, there exists a (measurable) function $D^*(P) : \mathcal{O} \rightarrow \mathbb{R}$ such that $E_P(D^*(P)(O)) = 0$, $\text{Var}_P(D^*(P)(O)) < \infty$, and, for every fluctuation $\{P_h : h \in H\}$ with score s at $h = 0$, the real-valued mapping $h \mapsto \Psi(P_h)$ is differentiable at $h = 0$, with a derivative equal to

$$E_P(D^*(P)(O)s(O)). \quad (3.3)$$

The object $D^*(P)$ in (3.3) is called a gradient of Ψ at P .²

¹That is, P_h is dominated by P : if an event A satisfies $P(A) = 0$, then necessarily $P_h(A) = 0$ too. Because $P_h \ll P$, the law P_h has a density with respect to P , meaning that there exists a (measurable) function f such that $P_h(A) = \int_{o \in A} f(o) dP(o)$ for any event A . The function is often denoted dP_h/dP .

²Interestingly, if a fluctuation $\{P_h : h \in H\}$ satisfies (3.2) for a direction s such that $s \neq 0$, $E_P(s(O)) = 0$ and $\text{Var}_P(s(O)) < \infty$, then $h \mapsto \Psi(P_h)$ is still differentiable at $h = 0$ with a derivative equal to (3.3) beyond fluctuations of the form (3.1).

3.3.3 A Euclidean perspective

This terminology has a direct parallel to directional derivatives in the calculus of Euclidean geometry. Recall that if f is a differentiable mapping from \mathbb{R}^p to \mathbb{R} , then the directional derivative of f at a point x (an element of \mathbb{R}^p) in direction u (a unit vector in \mathbb{R}^p) is the scalar product of the gradient of f and u . In words, the directional derivative of f at x can be represented as a scalar product of the direction that we approach x and the change of the function's value at x .

In the present problem, the law P is *the point* at which we evaluate the function Ψ , the score s of the fluctuation is *the direction* in which we approach the point, and the gradient describes the change in the function's value at the point.

3.3.4 The canonical gradient

In general, it is possible for many gradients to exist³. Yet, in the special case that the model is nonparametric, only a single gradient exists. The unique gradient is then referred to as *the canonical gradient* or *the efficient influence curve*, for reasons that will be clarified in Section 3.5. In the more general setting, the canonical gradient may be defined as the minimizer of $D \mapsto \text{Var}_P(D(O))$ over the set of all gradients.

It is not difficult to check that the efficient influence curve of statistical mapping Ψ (2.6) at $P \in \mathcal{M}$ can be written as

$$\begin{aligned} D^*(P) &\doteq D_1^*(P) + D_2^*(P), \quad \text{where} \\ D_1^*(P)(O) &\doteq \bar{Q}(1, W) - \bar{Q}(0, W) - \Psi(P), \\ D_2^*(P)(O) &\doteq \frac{2A - 1}{\ell \bar{G}(A, W)}(Y - \bar{Q}(A, W)). \end{aligned} \tag{3.4}$$

A method from package `tlrider` evaluates the efficient influence curve at a law described by an object of class `LAW`. It is called `evaluate_eic`. For instance, the next chunk of code evaluates the efficient influence curve $D^*(P_0)$ of Ψ (2.6) at $P_0 \in \mathcal{M}$ that is characterized by experiment:

```
eic_experiment <- evaluate_eic(experiment)
```

The efficient influence curve $D^*(P_0)$ is a function from \mathcal{O} to \mathbb{R} . As such, it can be evaluated at the five independent observations drawn from P_0 in Section 1.2.2. This is what the next chunk of code does:

³This may be at first surprising given the parallel drawn in Section 3.3.3 to Euclidean geometry. However, it is important to remember that the model dictates fluctuations of P that are valid submodels with respect to the full model. In turn, this determines the possible directions from which we may approach P . Thus, depending on the direction, (3.3) may hold with different choices of D^* .

```
(eic_experiment(five_obs))
#> [1] 0.246 -0.157 -0.534 -0.243 0.234
```

Finally, the efficient influence curve can be visualized as two images that represent $(w, y) \mapsto D^*(P_0)(w, a, y)$ for $a = 0, 1$, respectively:

```
crossing(w = seq(0, 1, length.out = 2e2),
  a = c(0, 1),
  y = seq(0, 1, length.out = 2e2)) %>%
  mutate(eic = eic_experiment(cbind(Y=y,A=a,W=w))) %>%
  ggplot(aes(x = w, y = y, fill = eic)) +
  geom_raster(interpolate = TRUE) +
  geom_contour(aes(z = eic), color = "white") +
  facet_wrap(~ a, nrow = 1,
    labeller = as_labeller(c(`0` = "a = 0", `1` = "a = 1")))) +
  labs(fill = expression(paste(D~"*", (P[0])(w,a,y))))
```

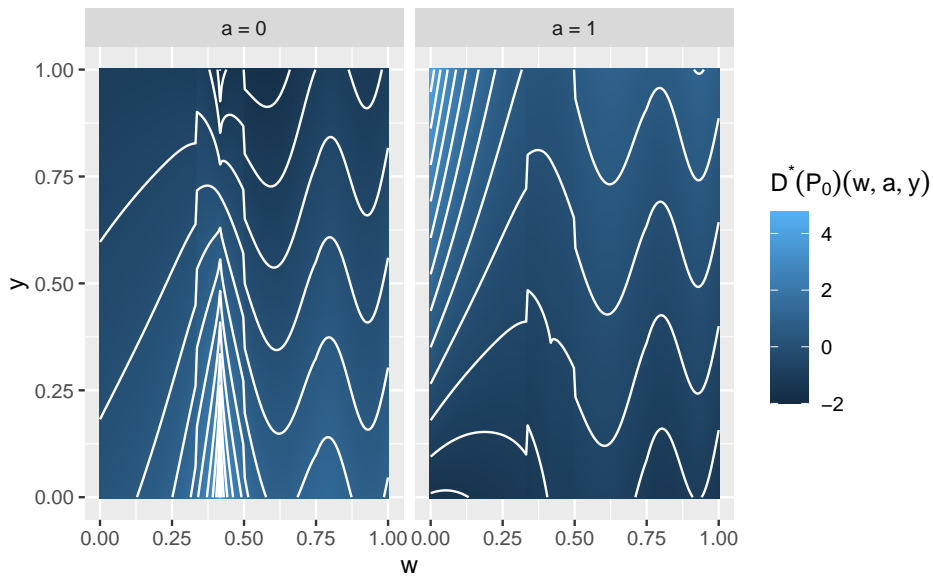


Figure 3.2: Visualizing the efficient influence curve $D^*(P_0)$ of Ψ (2.6) at P_0 , the law described by `experiment`.

3.4 A fresh look at `another_experiment`

We can give a fresh look at Section 3.1.2 now.

3.4.1 Deriving the efficient influence curve

It is not difficult (though cumbersome) to verify that, up to a constant, $\{\Pi_h : h \in [-1, 1]\}$ is a fluctuation of Π_0 in the direction (in the sense of (3.1)) of

$$\sigma_0(O) \doteq -10\sqrt{W}A \times \beta_0(A, W) \times \left(\log(1 - Y) + \sum_{k=0}^3 (k + \beta_0(A, W))^{-1} \right) + \text{constant}, \quad \text{where} \quad (3.5)$$

$$\beta_0(A, W) \doteq \frac{1 - \bar{Q}_{\Pi_0}(A, W)}{\bar{Q}_{\Pi_0}(A, W)}. \quad (3.6)$$

Consequently, the slope of line in Figure 3.1 is equal to

$$E_{\Pi_0}(D^*(\Pi_0)(O)\sigma_0(O)). \quad (3.7)$$

Since $D^*(\Pi_0)$ is centered under Π_0 , knowing σ_0 up to a constant is not problematic.

3.4.2 Numerical validation

In the following code, we check the above fact numerically. When we ran `example(tlrider)`, we created a function `sigma0`. The function implements σ_0 defined in (3.6):

```
sigma0
#> function(obs, law = another_experiment) {
#>   ## preliminary
#>   Qbar <- get_feature(law, "Qbar", h = 0)
#>   QAW <- Qbar(obs[, c("A", "W")])
#>   params <- formals(get_feature(law, "qY", h = 0))
#>   shape1 <- eval(params$shape1)
#>   ## computations
#>   betaAW <- shape1 * (1 - QAW) / QAW
#>   out <- log(1 - obs[, "Y"])
#>   for (int in 1:shape1) {
#>     out <- out + 1/(int - 1 + betaAW)
#>   }
#>   out <- - out * shape1 * (1 - QAW) / QAW *
#>     10 * sqrt(obs[, "W"]) * obs[, "A"]
#>   ## no need to center given how we will use it
#>   return(out)
#> }
```


The next chunk of code approximates (3.7) pointwise and with a confidence interval of asymptotic level 95%:

```
eic_another_experiment <- evaluate_eic(another_experiment, h = 0)
obs_another_experiment <- sample_from(another_experiment, B, h = 0)
vars <- eic_another_experiment(obs_another_experiment) *
  sigma0(obs_another_experiment)

sd_hat <- sd(vars)
(slope_hat <- mean(vars))
#> [1] 1.36
(slope_CI <- slope_hat + c(-1, 1) *
  qnorm(1 - alpha / 2) * sd_hat / sqrt(B))
#> [1] 1.35 1.36
```

Equal to 1.349 (rounded to three decimal places — hereafter, all rounding will be to three decimal places as well), the first numerical approximation `slope_approx` is not too off!

3.5 \supset Asymptotic linearity and statistical efficiency

3.5.1 Asymptotic linearity

Suppose that O_1, \dots, O_n are drawn independently from $P \in \mathcal{M}$. If an estimator ψ_n of $\Psi(P)$ can be written as

$$\psi_n = \Psi(P) + \frac{1}{n} \sum_{i=1}^n \text{IC}(O_i) + o_P(1/\sqrt{n}) \quad (3.8)$$

for some function $\text{IC} : \mathcal{O} \rightarrow \mathbb{R}$ such that $\mathbb{E}_P(\text{IC}(O)) = 0$ and $\text{Var}_P(\text{IC}(O)) < \infty$, then we say that ψ_n is *asymptotically linear* with *influence curve* IC . Asymptotically linear estimators are *weakly convergent*. Specifically, if ψ_n is asymptotically linear with influence curve IC , then

$$\sqrt{n}(\psi_n - \Psi(P)) = \frac{1}{\sqrt{n}} \sum_{i=1}^n \text{IC}(O_i) + o_P(1) \quad (3.9)$$

and, by the central limit theorem (recall that O_1, \dots, O_n are independent), $\sqrt{n}(\psi_n - \Psi(P))$ converges in law to a centered Gaussian distribution with variance $\text{Var}_P(\text{IC}(O))$.

3.5.2 Influence curves and gradients

As it happens, influence curves of regular⁴ estimators are intimately related to gradients. In fact, if ψ_n is a regular, asymptotically linear estimator of $\Psi(P)$ with influence curve IC, then it must be true that Ψ is smooth at P and that IC is a gradient of Ψ at P .

3.5.3 Asymptotic efficiency

Now recall that, in Section 3.3.4, we defined the canonical gradient as the minimizer of $D \mapsto \text{Var}_P(D(O))$ over the set of all gradients. Therefore, if ψ_n is a regular, asymptotically linear estimator of $\Psi(P)$ (built from n independent observations drawn from P), then the asymptotic variance of $\sqrt{n}(\psi_n - \Psi(P))$ cannot be smaller than the variance of the canonical gradient of Ψ at P , *i.e.*,

$$\text{Var}_P(D^*(P)(O)). \quad (3.10)$$

In other words, (3.10) is the lower bound on the asymptotic variance of *any* regular, asymptotically linear estimator of $\Psi(P)$. This bound is referred to as the *Cramér-Rao bound*. Any regular estimator that achieves this variance bound is said to be *asymptotically efficient* at P . Because the canonical gradient is the influence curve of an asymptotically efficient estimator, it is often referred to as the *efficient influence curve*.

3.6 Cramér-Rao bounds

1. What does the following chunk do?

```
obs <- sample_from(experiment, B)
(cramer_rao_hat <- var(eic_experiment(obs)))
#> [1] 0.287
```

2. Same question about this one.

```
obs_another_experiment <- sample_from(another_experiment, B, h = 0)
(cramer_rao_pi_zero_hat <-
  var(eic_another_experiment(obs_another_experiment)))
#> [1] 0.0957
```

⁴We can view ψ_n as the by product of an algorithm $\widehat{\Psi}$ trained on independent observations O_1, \dots, O_n drawn from P . We say that the estimator is regular at P if, for any direction $s \neq 0$ such that $E_P(s(O)) = 0$ and $\text{Var}_P(s(O)) < \infty$ and fluctuation $\{P_h : h \in H\}$ satisfying (3.2), the estimator $\psi_{n,1/\sqrt{n}}$ of $\Psi(P_{1/\sqrt{n}})$ obtained by training $\widehat{\Psi}$ on independent observations O_1, \dots, O_n drawn from $P_{1/\sqrt{n}}$ is such that $\sqrt{n}(\psi_{n,1/\sqrt{n}} - \Psi(P_{1/\sqrt{n}}))$ converges in law to a limit that does not depend on s .

3. With a large independent sample drawn from $\Psi(P_0)$ (or $\Psi(\Pi_0)$), is it possible to construct a regular estimator ψ_n of $\Psi(P_0)$ (or $\Psi(\Pi_0)$) such that the asymptotic variance of \sqrt{n} times ψ_n minus its target be smaller than the Cramér-Rao bound?
4. Is it easier to estimate $\Psi(P_0)$ or $\Psi(\Pi_0)$ (from independent observations drawn from either law)? In what sense? (Hint: you may want to compute a ratio.)

Section 4

Double-robustness

4.1 Linear approximations of parameters

4.1.1 From gradients to estimators

We learned in Section 3 that the stochastic behavior of a regular, asymptotically linear estimator of $\Psi(P)$ can be characterized by its influence curve. Moreover, we said that this influence curve must in fact be a gradient of Ψ at P .

In this section, we show that the converse is also true: given a gradient D^* of Ψ at P , under so-called *regularity conditions*, it is possible to construct an estimator with influence curve equal to $D^*(P)$. This fact will suggest concrete strategies for generating efficient estimators of smooth parameters. We take here the first step towards generating such estimators: linearizing the parameter.

4.1.2 A Euclidean perspective

As in Section 3.3.3, drawing a parallel to Euclidean geometry is helpful. We recall that if f is a differentiable mapping from \mathbb{R}^p to \mathbb{R} , then a Taylor series approximates f at a point $x_0 \in \mathbb{R}^p$:

$$f(x_0) \approx f(x) + \langle (x_0 - x), \nabla f(x) \rangle,$$

where x is a point in \mathbb{R}^p , $\nabla f(x)$ is the gradient of f evaluated at x and $\langle u, v \rangle$ is the scalar product of $u, v \in \mathbb{R}^p$. As the squared distance $\|x - x_0\|^2 = \langle x - x_0, x - x_0 \rangle$ between x and x_0 decreases, the *linear approximation* to $f(x_0)$ becomes more accurate.

4.1.3 The remainder term

Returning to the present problem with this in mind, we find that indeed a similar approximation strategy may be applied.

For clarity, let us introduce a new shorthand notation. For any measurable function f of the observed data O , we may write from now on $Pf \doteq \mathbb{E}_P(f(O))$. One may argue that the notation is valuable beyond the gain of space. For instance, (3.9)

$$\sqrt{n}(\psi_n - \Psi(P)) = \frac{1}{\sqrt{n}} \sum_{i=1}^n \text{IC}(O_i) + o_P(1)$$

can be rewritten as

$$\sqrt{n}(\psi_n - \Psi(P)) = \sqrt{n}(P_n - P)\text{IC} + o_P(1),$$

thus suggesting more clearly the importance of the so-called *empirical process* $\sqrt{n}(P_n - P)$. In particular, if Ψ is smooth uniformly over directions, then for any given $P \in \mathcal{M}$, we can write

$$\Psi(P_0) = \Psi(P) + (P_0 - P)D^*(P) - \text{Rem}_{P_0}(P), \quad (4.1)$$

where $\text{Rem}_{P_0}(P)$ (defined *implicitly* by (4.1) – see (4.2)) is a *remainder term* satisfying that

$$\frac{\text{Rem}_{P_0}(P)}{d(P, P_0)} \rightarrow 0 \text{ as } d(P, P_0) \rightarrow 0,$$

with d a measure of discrepancy for distributions in \mathcal{M} . Note that (4.1) can be equivalently written as

$$\Psi(P_0) = \Psi(P) + \mathbb{E}_{P_0}(D^*(P)(O)) - \mathbb{E}_P(D^*(P)(O)) - \text{Rem}_{P_0}(P).$$

The remainder term formalizes the notion that if P is *close* to P_0 (*i.e.*, if $d(P, P_0)$ is small), then the linear approximation of $\Psi(P_0)$ is more accurate.

4.1.4 Expressing the remainder term as a function of the relevant features

The equations for the definition of the parameter (2.6), form of the canonical gradient (3.4), and linearization of parameter (4.1) combine to determine the remainder:

$$\text{Rem}_{P_0}(P) \doteq \Psi(P) - \Psi(P_0) - (P_0 - P)D^*(P) \quad (4.2)$$

hence

$$\text{Rem}_{P_0}(P) = \mathbb{E}_{P_0} \left[\left(\bar{G}_0(W) - \bar{G}(W) \right) \times \left(\frac{\bar{Q}_0(1, W) - \bar{Q}(1, W)}{\ell \bar{G}(1, W)} + \frac{\bar{Q}_0(0, W) - \bar{Q}(0, W)}{\ell \bar{G}(0, W)} \right) \right]. \quad (4.3)$$

Acting as oracles, we can compute explicitly the remainder term $\text{Rem}_{P_0}(P)$. The `evaluate_remainder` method makes it very easy (simply run `?evaluate_remainder` to see the man page of the method):

```
(evaluate_remainder(experiment, experiment))
#> [1] 0
(rem <- evaluate_remainder(experiment, another_experiment,
                           list(list(), list(h = 0))))
#> [1] 0.199
```

We recover the equality $\text{Rem}_{P_0}(P_0) = 0$, which is fairly obvious given (4.1). In addition, we learn that $\text{Rem}_{P_0}(\Pi_0)$ equals 0.199. In the next subsection, we invite you to make better acquaintance with the remainder term by playing around with it numerically.

4.2 The remainder term

1. Compute numerically $\text{Rem}_{\Pi_0}(\Pi_h)$ for $h \in [-1, 1]$ and plot your results. What do you notice?
2. Approximate $\text{Rem}_{P_0}(\Pi_0)$ numerically without relying on method `evaluate_remainder` and compare the value you get with that of `rem`. (Hint: use (4.2) and a large sample of observations drawn independently from P_0 .)

4.3 Double-robustness

4.3.1 The key property

Let us denote by $\|f\|_P^2$ the square of the $L^2(P)$ -norm of any function f from \mathcal{O} to \mathbb{R} *i.e.*, using a recently introduced notation, $\|f\|_P^2 \doteq P f^2$. For instance, $\|\bar{Q}_1 - \bar{Q}_0\|_P$ or $\|\bar{G}_1 - \bar{G}_0\|_P$ is a distance separating the features \bar{Q}_1 and \bar{Q}_0 or \bar{G}_1 and \bar{G}_0 .

The efficient influence curve $D^*(P)$ at $P \in \mathcal{M}$ enjoys a rather remarkable property: it is *double-robust*. Specifically, for every $P \in \mathcal{M}$, the remainder term $\text{Rem}_{P_0}(P)$ satisfies

$$\text{Rem}_{P_0}(P)^2 \leq \|\bar{Q} - \bar{Q}_0\|_{P_0}^2 \times \|(\bar{G} - \bar{G}_0)/\ell \bar{G}_0\|_{P_0}^2, \quad (4.4)$$

where \bar{Q} and \bar{G} are the counterparts under P to \bar{Q}_0 and \bar{G}_0 . The proof consists in a straight-forward application of the Cauchy-Schwarz inequality to the right-hand side expression in (4.2).

4.3.2 Its direct consequence

It may not be clear yet why (4.4) is an important property, and why D^* is said *double-robust* because of it. To answer the latter question, let us consider a law $P \in \mathcal{M}$ such that *either* $\bar{Q} = \bar{Q}_0$ *or* $\bar{G} = \bar{G}_0$.

It is then the case that *either* $\|\bar{Q} - \bar{Q}_0\|_P = 0$ *or* $\|\bar{G} - \bar{G}_0\|_P = 0$. Therefore, in light of (4.4), it also holds that $\text{Rem}_{P_0}(P) = 0$.¹ It thus appears that (4.1) simplifies to

$$\begin{aligned}\Psi(P_0) &= \Psi(P) + (P_0 - P)D^*(P) \\ &= \Psi(P) + P_0D^*(P),\end{aligned}$$

where the second equality holds because $PD^*(P) = 0$ for all $P \in \mathcal{M}$ by definition of $D^*(P)$.

It is now clear that for such a law $P \in \mathcal{M}$, $\Psi(P) = \Psi(P_0)$ is equivalent to

$$P_0D^*(P) = 0. \tag{4.5}$$

Most importantly, in words, if P solves the so-called P_0 -specific efficient influence curve equation (4.5) and if, in addition, P has the same \bar{Q} -feature *or* \bar{G} -feature as P_0 , then $\Psi(P) = \Psi(P_0)$.

The conclusion is valid no matter how P may differ from P_0 otherwise, hence the notion of being *double-robust*. This property is useful to build consistent estimators of $\Psi(P)$, as we shall see in Section 5.

4.4 Double-robustness

1. Go back to Problem 1 in 4.2. In light of Section 4.3, what is happening?
2. Create a copy of `experiment` and replace its `Gbar` feature with some other function of W (see `?copy`, `?alter` and Problem 2 in Section 3.2). Call P' the element of model \mathcal{M} thus characterized. Can you guess the values of $\text{Rem}_{P_0}(P')$, $\Psi(P')$ and $P_0D^*(P')$? Support your argument.

¹This also trivially follows from (4.3).

Section 5

Inference

5.1 Where we stand

In the previous sections, we analyzed our target parameter and presented relevant theory for understanding the statistical properties of certain types of estimators of the parameter. The theory is also relevant for building and comparing a variety of estimators.

We assume from now on that we have available a sample O_1, \dots, O_B of independent observations drawn from P_0 . This is literally the case!, and the observations are stored in `obs` that we created in Section 3.6.

```
iter <- 1e3
```

Equal to 1 million, the sample size `B` is very large. We will in fact use 1000 disjoint subsamples composed of n independent observations among O_1, \dots, O_B , where n equals `B/iter`, *i.e.*, 1000. We will thus be in a position to investigate the statistical properties of every estimation procedure by replicating it independently 1000 times.

5.2 Where we go

The following sections explore different statistical paths to inferring ψ_0 or, rather (though equivalently), $\Psi(P_0)$.

- Section 6 presents a simple inference strategy. It can be carried out in situations where \bar{G}_0 is already known to the statistician.
- Section 7 discusses the estimation of some infinite-dimensional features of P_0 . The resulting estimators are later used to estimate ψ_0 .
- Section 8 extends the inference strategy discussed in Section 6 to the case that \bar{G}_0 is not known to the statistician but estimated by her. It also presents another inference

strategy that relies upon the estimation of \bar{Q}_0 . A theoretical analysis reveals that both strategies, called the *inverse probability of treatment weighted* and *G-computation* estimation methodologies, suffer from an inherent flaw.

- Section 9 builds upon the aforementioned analysis and develops a methodological workaround to circumvent the problem revealed by the analysis. It appears indeed that the flawed estimators can be corrected. However, the so-called *one-step correction* comes at a price that may be high in small samples.
- Section 10 also builds on the aforementioned analysis but draws a radically different conclusion from it. Instead of trying to circumvent the problem by correcting the flawed estimators of ψ_0 , it does so by correcting the estimators of the infinite-dimensional features of P_0 combined to estimate ψ_0 . The section thus presents an instantiation of the general *targeted minimum loss estimation* procedure tailored to the estimation of ψ_0 . It is the main destination of this ride in targeted learning territory, far from its outposts yet well into this exciting territory.

Section 6

A simple inference strategy

6.1 A cautionary detour

Let us introduce first the following estimator:

$$\begin{aligned}\psi_n^a &\doteq \frac{E_{P_n}(AY)}{E_{P_n}(A)} - \frac{E_{P_n}((1-A)Y)}{E_{P_n}(1-A)} \\ &= \frac{\sum_{i=1}^n \mathbf{1}\{A_i = Y_i = 1\}}{\sum_{i=1}^n \mathbf{1}\{A_i = 1\}} - \frac{\sum_{i=1}^n \mathbf{1}\{A_i = 0, Y_i = 1\}}{\sum_{i=1}^n \mathbf{1}\{A_i = 0\}}.\end{aligned}\tag{6.1}$$

It estimates

$$\begin{aligned}\Phi(P_0) &\doteq \frac{E_{P_0}(AY)}{E_{P_0}(A)} - \frac{E_{P_0}((1-A)Y)}{E_{P_0}(1-A)} \\ &= E_{P_0}(Y|A=1) - E_{P_0}(Y|A=0).\end{aligned}$$

We seize this opportunity to demonstrate numerically the obvious fact that ψ_n^a *does not* estimate $\Psi(P_0)$ because, in general, $\Psi(P_0)$ and $\Phi(P_0)$ differ. This is apparent in the following alternative expression of $\Phi(P_0)$:

$$\begin{aligned}\Phi(P_0) &= E_{P_0} \left(E_{P_0}(Y | A, W) | A = 1 \right) - E_{P_0} \left(E_{P_0}(Y | A, W) | A = 0 \right) \\ &= \int \bar{Q}_0(1, w) dP_{0, W|A=1}(w) - \int \bar{Q}_0(0, w) dP_{0, W|A=0}(w).\end{aligned}$$

Contrast the above equalities and (2.1). In the latter, the outer integral is against the marginal law of W under P_0 . In the former, the outer integrals are respectively against the conditional laws of W given $A = 1$ and $A = 0$ under P_0 .

6.2 Delta-method

Consider the next chunk of code:

```
compute_irrelevant_estimator <- function(obs) {
  obs <- as_tibble(obs)
  Y <- pull(obs, Y)
  A <- pull(obs, A)
  psi_n <- mean(A * Y) / mean(A) - mean((1 - A) * Y) / mean(1 - A)
  Var_n <- cov(cbind(A * Y, A, (1 - A) * Y, (1 - A)))
  phi_n <- c(1 / mean(A), -mean(A * Y) / mean(A)^2,
            -1 / mean(1 - A),
            mean((1 - A) * Y) / mean(1 - A)^2)
  var_n <- as.numeric(t(phi_n) %*% Var_n %*% phi_n)
  sig_n <- sqrt(var_n / nrow(obs))
  tibble(psi_n = psi_n, sig_n = sig_n)
}
```

Function `compute_irrelevant_estimator` computes the estimator ψ_n^a (6.1) based on the data set in `obs`.

Introduce $X_n \doteq n^{-1} \sum_{i=1}^n (A_i Y_i, A_i, (1 - A_i) Y_i, 1 - A_i)^\top$ and $X \doteq (AY, A, (1 - A)Y, 1 - A)^\top$. It happens that X_n is asymptotically Gaussian: as n goes to infinity,

$$\sqrt{n} (X_n - E_{P_0}(X))$$

converges in law to the centered Gaussian law with covariance matrix

$$V_0 \doteq E_{P_0} \left((X - E_{P_0}(X)) \times (X - E_{P_0}(X))^\top \right).$$

Let $f : \mathbb{R} \times \mathbb{R}^* \times \mathbb{R} \times \mathbb{R}^*$ be given by $f(r, s, t, u) = r/s - t/u$. The function is differentiable.

1. Check that $\psi_n^a = f(X_n)$. Point out the line where ψ_n^a is computed in the body of `compute_irrelevant_estimator`. Also point out to the line where the above asymptotic variance of X_n is estimated with its empirical counterpart, say V_n .
2. Argue how the delta-method yields that $\sqrt{n}(\psi_n^a - \Phi(P_0))$ converges in law to the centered Gaussian law with a variance that can be estimated with

$$v_n^a \doteq \nabla f(X_n) \times V_n \times \nabla f(X_n)^\top. \quad (6.2)$$

3. Check that the gradient ∇f of f is given by $\nabla f(r, s, t, u) \doteq (1/s, -r/s^2, -1/u, t/u^2)$. Point out to the line where the asymptotic variance of ψ_n^a is estimated.

For instance,

```
(compute_irrelevant_estimator(head(obs, 1e3)))
#> # A tibble: 1 x 2
#>   psi_n sig_n
#>   <dbl> <dbl>
#> 1 0.110 0.0173
```

computes the numerical values of ψ_n^a and v_n^a based on the 1000 first observations in `obs`.

6.3 IPTW estimator assuming the mechanism of action known

6.3.1 A simple estimator

Let us assume for a moment that we know \bar{G}_0 . This would have been the case indeed if P_0 were a controlled experiment. Note that, on the contrary, assuming \bar{Q}_0 known would be difficult to justify.

```
Gbar <- get_feature(experiment, "Gbar")
```

The alternative expression (2.7) suggests to estimate $\Psi(P_0)$ with

$$\psi_n^b \doteq \mathbb{E}_{P_n} \left(\frac{2A - 1}{\ell \bar{G}_0(A, W)} Y \right) \quad (6.3)$$

$$= \frac{1}{n} \sum_{i=1}^n \left(\frac{2A_i - 1}{\ell \bar{G}_0(A_i, W_i)} Y_i \right). \quad (6.4)$$

Note how P_n is substituted for P_0 in (6.4) relative to (2.7). However, we cannot call ψ_n^b a *substitution estimator* because it does not write as Ψ evaluated at an element of \mathcal{M} . This said, it is dubbed an IPTW (inverse probability of treatment weighted) estimator because of the denominators $\ell \bar{G}_0(A_i, W_i)$ in its definition.¹

In Section 8.2, we develop another IPTW estimator that does not assume that \bar{G}_0 is known beforehand.

6.3.2 Elementary statistical properties

It is easy to check that ψ_n^b estimates $\Psi(P_0)$ consistently, but this is too little to request from an estimator of ψ_0 . Better, ψ_n^b also satisfies a central limit theorem: $\sqrt{n}(\psi_n^b - \psi_0)$

¹We could have used the alternative expression IPAW, where A (like action) is substituted for T (like treatment).

converges in law to a centered Gaussian law with asymptotic variance

$$v^b \doteq \text{Var}_{P_0} \left(\frac{2A-1}{\ell \bar{G}_0(A, W)} Y \right),$$

where v^b can be consistently estimated by its empirical counterpart

$$v_n^b \doteq \text{Var}_{P_n} \left(\frac{2A-1}{\ell \bar{G}_0(A, W)} Y \right) \quad (6.5)$$

$$= \frac{1}{n} \sum_{i=1}^n \left(\frac{2A_i-1}{\ell \bar{G}_0(A_i, W_i)} Y_i - \psi_n^b \right)^2. \quad (6.6)$$

We investigate *empirically* the statistical behavior of ψ_n^b in Section 6.3.3.

6.3.3 Empirical investigation

The package `tlrider` includes `compute_ipwtw`, a function that implements the IPTW inference strategy (simply run `?compute_ipwtw` to see its man page). For instance,

```
(compute_ipwtw(head(obs, 1e3), Gbar))
#> # A tibble: 1 x 2
#>   psi_n sig_n
#>   <dbl> <dbl>
#> 1 0.0713 0.0556
```

computes the numerical values of ψ_n^b and v_n^b based upon the 1000 first observations contained in `obs`.

The next chunk of code investigates the empirical behaviors of estimators ψ_n^a and ψ_n^b . As explained in Section 5, we first make `iter` data sets out of the `obs` data set (second line), then build the estimators on each of them (fourth and fifth lines). After the first series of commands the object `psi_hat_ab`, a `tibble`, contains 2000 rows and four columns. For each smaller data set (identified by its `id`), two rows contain the values of either ψ_n^a and $\sqrt{v_n^a}/\sqrt{n}$ (if `type` equals `a`) or ψ_n^b and $\sqrt{v_n^b}/\sqrt{n}$ (if `type` equals `b`).

After the second series of commands, the object `psi_hat_ab` contains, in addition, the values of the recentered (with respect to ψ_0) and renormalized $\sqrt{n}/\sqrt{v_n^a}(\psi_n^a - \psi_0)$ and $\sqrt{n}/\sqrt{v_n^b}(\psi_n^b - \psi_0)$, where v_n^a (6.2) and v_n^b (6.5) estimate the asymptotic variances of ψ_n^a and ψ_n^b , respectively. Finally, `bias_ab` reports amounts of bias (at the renormalized scale).

We will refer to the recentering (always with respect to ψ_0) then renormalizing procedure as a *renormalization scheme*, because what may vary between two such procedures is the renormalization factor. We will judge whether or not the renormalization scheme is adequate for instance by comparing kernel density estimators of the law of estimators gone through a renormalization procedure with the standard normal density, as in Figure 6.1 below.

```

psi_hat_ab <- obs %>% as_tibble %>%
  mutate(id = (seq_len(n()) - 1) %% iter) %>%
  nest(obs = c(W, A, Y)) %>%
  mutate(est_a = map(obs, ~ compute_irrelevant_estimator(.)),
         est_b = map(obs, ~ compute_iprw(as.matrix(.), Gbar))) %>%
  pivot_longer(c(`est_a`, `est_b`),
              names_to = "type", values_to = "estimates") %>%
  extract(type, "type", "_(ab)$") %>%
  unnest(estimates) %>% select(-obs)

(psi_hat_ab)
#> # A tibble: 2,000 x 4
#>       id type  psi_n sig_n
#>   <dbl> <chr> <dbl> <dbl>
#> 1     0 a    0.0942 0.0171
#> 2     0 b    0.0169 0.0573
#> 3     1 a    0.105  0.0164
#> 4     1 b    0.0520 0.0551
#> 5     2 a    0.111  0.0187
#> 6     2 b    0.135  0.0546
#> # ... with 1,994 more rows

psi_hat_ab <- psi_hat_ab %>%
  group_by(id) %>%
  mutate(clt = (psi_n - psi_zero) / sig_n)

(psi_hat_ab)
#> # A tibble: 2,000 x 5
#> # Groups:   id [1,000]
#>       id type  psi_n sig_n clt
#>   <dbl> <chr> <dbl> <dbl> <dbl>
#> 1     0 a    0.0942 0.0171 0.643
#> 2     0 b    0.0169 0.0573 -1.16
#> 3     1 a    0.105  0.0164 1.30
#> 4     1 b    0.0520 0.0551 -0.565
#> 5     2 a    0.111  0.0187 1.49
#> 6     2 b    0.135  0.0546 0.952
#> # ... with 1,994 more rows

(bias_ab <- psi_hat_ab %>%
  group_by(type) %>% summarise(bias = mean(clt)))
#> # A tibble: 2 x 2

```

```

#>   type    bias
#>   <chr> <dbl>
#> 1 a     1.40
#> 2 b     0.0353

fig_bias_ab <- ggplot() +
  geom_line(aes(x = x, y = y),
            data = tibble(x = seq(-3, 3, length.out = 1e3),
                          y = dnorm(x)),
            linetype = 1, alpha = 0.5) +
  geom_density(aes(colt, fill = type, colour = type),
              psi_hat_ab, alpha = 0.1) +
  geom_vline(aes(xintercept = bias, colour = type),
            bias_ab, size = 1.5, alpha = 0.5)

fig_bias_ab +
  labs(y = "",
       x = bquote(paste(sqrt(n/v[n]^{list(a, b)}) *
                       (psi[n]^{list(a, b)} - psi[0]))))

```

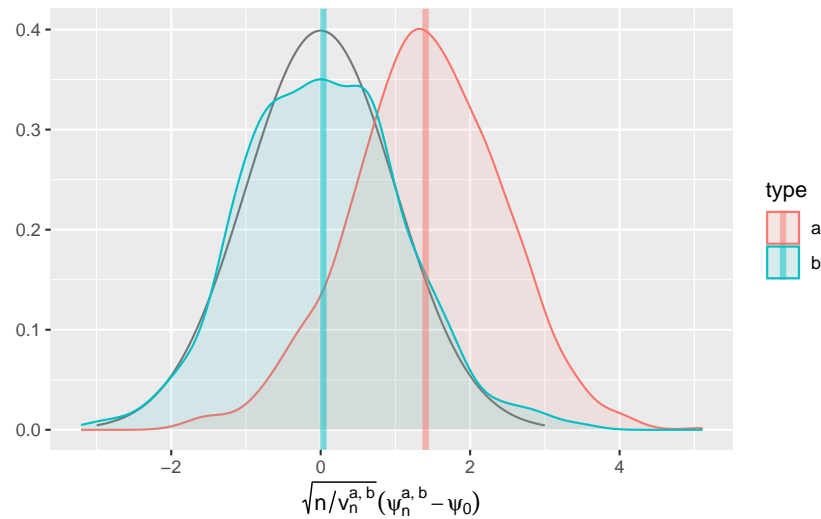


Figure 6.1: Kernel density estimators of the law of two estimators of ψ_0 (recentred with respect to ψ_0 , and renormalized), one of them misconceived (a), the other assuming that \bar{G}_0 is known (b). Built based on `iter` independent realizations of each estimator.

By the above chunk of code, the averages of $\sqrt{n/v_n^a}(\psi_n^a - \psi_0)$ and $\sqrt{n/v_n^b}(\psi_n^b - \psi_0)$ computed across the realizations of the two estimators are respectively equal to 1.404 and 0.035 (see `bias_ab`). Interpreted as amounts of bias, those two quantities are represented

by vertical lines in Figure 6.1. The red and blue bell-shaped curves represent the empirical laws of ψ_n^a and ψ_n^b (recentered with respect to ψ_0 , and renormalized) as estimated by kernel density estimation. The latter is close to the black curve, which represents the standard normal density.

Section 7

Nuisance parameters

7.1 Anatomy of an expression

From now, all the inference strategies that we will present unfold in two or three stages. For all of them, the first stage consists in estimating a selection of features of the law P_0 of the experiment. Specifically, the features are chosen among $Q_{0,W}$ (the marginal law of W under P_0), \bar{G}_0 (the conditional probability that $A = 1$ given W under P_0) and \bar{Q}_0 (the conditional mean of Y given A and W under P_0).

In this context, because they are not the parameter of primary interest (*i.e.*, they are not the real-values feature $\Psi(P_0)$), they are often referred to as *nuisance parameters* of P_0 . The unflattering expression conveys the notion that their estimation is merely an intermediate step along our path towards an inference of the target parameter.

As for the reason why $Q_{0,W}$, \bar{G}_0 and \bar{Q}_0 are singled out, it is because of their role in the definition of Ψ and the efficient influence curve $D^*(P_0)$.

7.2 An algorithmic stance

In general, we can view an estimator of any feature f_0 of P_0 as the output of an algorithm $\hat{\mathcal{A}}$ that maps any element of

$$\mathcal{M}^{\text{empirical}} \doteq \left\{ \frac{1}{m} \sum_{i=1}^m \text{Dirac}(o_i) : m \geq 1, o_1, \dots, o_m \in [0, 1] \times \{0, 1\} \times [0, 1] \right\}$$

to the set \mathcal{F} where f_0 is known to live. Here, $\mathcal{M}^{\text{empirical}}$ can be interpreted as the set of all possible empirical measures summarizing the outcomes of any number of replications of the experiment P_0 . In particular, P_n belongs to this set.

The `tlrider` package includes such template algorithms for the estimation of $Q_{0,W}$, \bar{G}_0 and \bar{Q}_0 . We illustrate how they work and their use in the next sections.

7.3 QW

For instance, `estimate_QW` is an algorithm $\widehat{\mathcal{A}}_{Q_W}$ for the estimation of the marginal law of W under P_0 (to see its man page, simply run `?estimate_QW`). It is a map from $\mathcal{M}^{\text{empirical}}$ to the set of laws on $[0, 1]$. The following chunk of code estimates $Q_{0,W}$ based on the $n = 1000$ first observations in `obs`:

```
QW_hat <- estimate_QW(head(obs, 1e3))
```

It is easy to sample independent observations from `QW_hat`. To do so, we create an object of class `LAW` then set its marginal law of W to that described by `QW_hat` and specify its `sample_from` feature:

```
empirical_experiment <- LAW()
alter(empirical_experiment, QW = QW_hat)
alter(empirical_experiment, sample_from = function(n) {
  QW <- get_feature(empirical_experiment, "QW")
  W <- sample(pull(QW, "value"), n, prob = pull(QW, "weight"))
  cbind(W = W, A = NA, Y = NA)
})
W <- sample_from(empirical_experiment, 1e3) %>% as_tibble

W %>%
  ggplot() +
    geom_histogram(aes(x = W, y = stat(density)), bins = 40) +
    stat_function(fun = get_feature(experiment, "QW"), col = "red")
```

Note that all the W s sampled from `QW_hat` fall in the set $\{W_1, \dots, W_n\}$ of observed W s in `obs` (an obvious fact given the definition of the `sample_from` feature of `empirical_experiment`:

```
(length(intersect(pull(W, W), head(obs[, "W"], 1e3))))
#> [1] 1000
```

This is because `estimate_QW` estimates $Q_{0,W}$ with its empirical counterpart, *i.e.*,

$$\frac{1}{n} \sum_{i=1}^n \text{Dirac}(W_i).$$

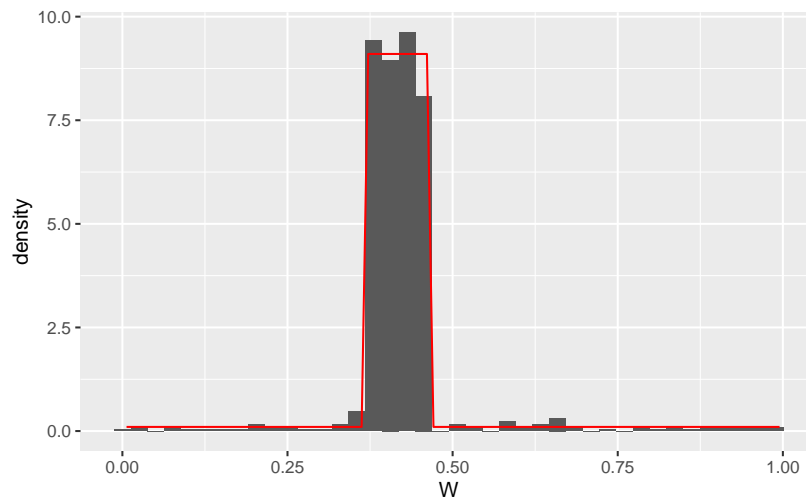


Figure 7.1: Histogram representing 1000 observations drawn independently from QW_hat . The superimposed red curve is the true density of $Q_{0,W}$.

7.4 Gbar

Another template algorithm is built-in into `tlrider`: `estimate_Gbar` (to see its man page, simply run `?estimate_Gbar`). Unlike `estimate_QW`, `estimate_Gbar` needs further specification of the algorithm. The package also includes examples of such specifications.

There are two sorts of specifications, of which we say that they are either *working model-based* or *machine learning-based*. We discuss the former sort in the next subsection. The latter sort is discussed in Section 7.6.

7.4.1 Working model-based algorithms

Let us take a look at `working_model_G_one` for instance:

```
working_model_G_one
#> $model
#> function (...)
#> {
#>   trim_glm_fit(glm(family = binomial(), ...))
#> }
#> <environment: 0xecf7498>
#>
#> $formula
#> A ~ I(W^0.5) + I(abs(W - 5/12)^0.5) + I(W^1) + I(abs(W - 5/12)^1) +
#>   I(W^1.5) + I(abs(W - 5/12)^1.5)
```

```
#> <environment: 0xecf7498>
#>
#> $type_of_preds
#> [1] "response"
#>
#> attr(,"ML")
#> [1] FALSE
```

and focus on its `model` and `formula` attributes. The former relies on the `glm` and `binomial` functions from `base R`, and on `trim_glm_fit` (which removes information that we do not need from the standard output of `glm`, simply run `?trim_glm_fit` to see the function's man page). The latter is a `formula` that characterizes what we call a *working model* for \bar{G}_0 .

In words, by using `working_model_G_one` we implicitly choose the so-called logistic (or negative binomial) loss function L_a given by

$$-L_a(f)(A, W) \doteq A \log f(W) + (1 - A) \log(1 - f(W)) \quad (7.1)$$

for any function $f : [0, 1] \rightarrow [0, 1]$ paired with the working model

$$\mathcal{F}_1 \doteq \{f_\theta : \theta \in \mathbb{R}^5\}$$

where, for any $\theta \in \mathbb{R}^5$,

$$\text{logit } f_\theta(W) \doteq \theta_0 + \sum_{j=1}^4 \theta_j W^{j/2}.$$

We acted as oracles when we specified the working model: it is *well-specified*, i.e., it happens that \bar{G}_0 is the unique minimizer of the risk entailed by L_a over \mathcal{F}_1 :

$$\bar{G}_0 = \arg \min_{f_\theta \in \mathcal{F}_1} \mathbb{E}_{P_0} (L_a(f_\theta)(A, W)).$$

Therefore, the estimator \bar{G}_n obtained by minimizing the empirical risk

$$\mathbb{E}_{P_n} (L_a(f_\theta)(A, W)) = \frac{1}{n} \sum_{i=1}^n L_a(f_\theta)(A_i, W_i)$$

over \mathcal{F}_1 estimates \bar{G}_0 consistently.

Of course, it is seldom certain in real life that the target feature, here \bar{G}_0 , belongs to the working model.¹ Suppose for instance that we choose a small finite-dimensional working model \mathcal{F}_2 without acting as an oracle. Then consistency certainly fails to hold. However, if \bar{G}_0 can nevertheless be *projected* unambiguously onto \mathcal{F}_2 (an assumption that cannot be checked), then the estimator might converge to the projection.

¹In fact, if one knows nothing about the feature, then it is *certain* that it does not belong to whichever small finite-dimensional working model we may come up with.

7.4.2 Visualization

To illustrate the use of the algorithm $\widehat{\mathcal{A}}_{\bar{G},1}$ obtained by combining `estimate_Gbar` and `working_model_G_one`, let us estimate \bar{G}_0 based on the first $n = 1000$ observations in `obs`:

```
Gbar_hat <- estimate_Gbar(head(obs, 1e3), algorithm = working_model_G_one)
```

Using `compute_Gbar_hat_W`² (simply run `?compute_Gbar_hat_W` to see its man page) makes it easy to compare visually the estimator $\bar{G}_n \doteq \widehat{\mathcal{A}}_{\bar{G},1}(P_n)$ with its target \bar{G}_0 :

```
tibble(w = seq(0, 1, length.out = 1e3)) %>%
  mutate("truth" = Gbar(w),
         "estimated" = compute_Gbar_hatW(w, Gbar_hat)) %>%
  pivot_longer(~w, names_to = "f", values_to = "value") %>%
  ggplot() +
  geom_line(aes(x = w, y = value, color = f), size = 1) +
  labs(y = "f(w)",
       title = bquote("Visualizing" ~ bar(G)[0] ~ "and" ~ hat(G)[n])) +
  ylim(NA, 1)
```

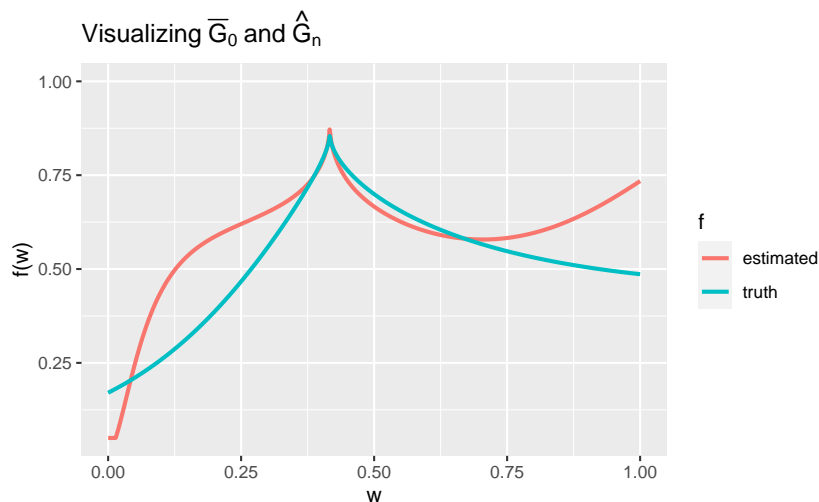


Figure 7.2: Comparing $\bar{G}_n \doteq \widehat{\mathcal{A}}_{\bar{G},1}(P_n)$ and \bar{G}_0 . The estimator is consistent because the algorithm relies on a working model that is correctly specified.

²See also the companion function `compute_lGbar_hat_AW` (run `?compute_lGbar_hat_AW` to see its man page).

7.5 Qbar, working model-based algorithms

A third template algorithm is built-in into `tlrider`: `estimate_Qbar` (to see its man page, simply run `?estimate_Qbar`). Like `estimate_Gbar`, `estimate_Qbar` needs further specification of the algorithm. The package also includes examples of such specifications, which can also be either working model-based (see Section 7.4) or machine learning-based (see Sections 7.6 and 7.7).

There are built-in specifications similar to `working_model_G_one`, *e.g.*,

```
working_model_Q_one
#> $model
#> function (...)
#> {
#>   trim_glm_fit(glm(family = binomial(), ...))
#> }
#> <environment: 0xecf7498>
#>
#> $formula
#> Y ~ A * (I(W~0.5) + I(W~1) + I(W~1.5))
#> <environment: 0xecf7498>
#>
#> $type_of_preds
#> [1] "response"
#>
#> attr("ML")
#> [1] FALSE
#> attr("stratify")
#> [1] FALSE
```

1. Drawing inspiration from Section 7.4, comment upon and use the algorithm $\widehat{\mathcal{A}}_{\bar{Q},1}$ obtained by combining `estimate_Gbar` and `working_model_Q_one`.

7.6 Qbar

7.6.1 Qbar, machine learning-based algorithms

We explained how algorithm $\widehat{\mathcal{A}}_{\bar{G},1}$ is based on a working model (and *you* did for $\widehat{\mathcal{A}}_{\bar{Q},1}$). It is not the case that all algorithms are based on working models in the same (admittedly rather narrow) sense. We propose to say that those algorithms that are not based on working models like $\widehat{\mathcal{A}}_{\bar{G},1}$, for instance, are instead *machine learning-based*.

Typically, machine learning-based algorithms are more data-adaptive; they rely on larger

working models, and/or fine-tune parameters that must be calibrated, *e.g.* by cross-validation. Furthermore, they call for being stacked, *i.e.*, combined by means of another outer algorithm (involving cross-validation) into a more powerful machine learning-based *meta-algorithm*. The super learning methodology is a popular stacking algorithm.

We will elaborate further on this important topic in another forthcoming part. Here, we merely illustrate the concept with two specifications built-in into `tlrider`. Based on the *k-nearest neighbors* non-parametric estimating methodology, the first one is discussed in the next subsection. Based on *boosted trees*, another non-parametric estimating methodology, the second one is used in the exercise that follows the next subsection.

7.6.2 Qbar, kNN algorithm

Algorithm $\widehat{\mathcal{A}}_{\bar{Q}, \text{kNN}}$ is obtained by combining `estimate_Qbar` and `kknn_algo`. The training of $\widehat{\mathcal{A}}_{\bar{Q}, \text{kNN}}$ (*i.e.*, the making of the output $\widehat{\mathcal{A}}_{\bar{Q}, \text{kNN}}(P_n)$) is implemented based on function `caret::train` of the `caret` (classification and regression training) package (to see its man page, simply run `?caret::train`). Some additional specifications are provided in `kknn_grid` and `kknn_control`.

In a nutshell, $\widehat{\mathcal{A}}_{\bar{Q}, \text{kNN}}$ estimates $\bar{Q}_0(1, \cdot)$ and $\bar{Q}_0(0, \cdot)$ separately. Each of them is estimated by applying the *k-nearest neighbors* methodology as it is implemented in function `kknn::train.kknn` from the `kknn` package (to see its man page, simply run `?kknn::train.kknn`).³ The following chunk of code trains algorithm $\widehat{\mathcal{A}}_{\bar{Q}, \text{kNN}}$ on P_n :

```
Qbar_hat_kknn <- estimate_Qbar(head(obs, 1e3),
                              algorithm = kknn_algo,
                              trControl = kknn_control,
                              tuneGrid = kknn_grid)
```

Using `compute_Qbar_hat_AW` (simply run `?compute_Qbar_hat_AW` to see its man page) makes it is easy to compare visually the estimator $\bar{Q}_{n, \text{kNN}} \doteq \widehat{\mathcal{A}}_{\bar{Q}, \text{kNN}}(P_n)$ with its target \bar{Q}_0 , see Figure 7.3.

```
fig <- tibble(w = seq(0, 1, length.out = 1e3),
              truth_1 = Qbar(cbind(A = 1, W = w)),
              truth_0 = Qbar(cbind(A = 0, W = w)),
              kNN_1 = compute_Qbar_hatAW(1, w, Qbar_hat_kknn),
              kNN_0 = compute_Qbar_hatAW(0, w, Qbar_hat_kknn))
```

³Specifically, argument `kmax` (maximum number of neighbors considered) is set to 5, argument `distance` (parameter of the Minkowski distance) is set to 2, and argument `kernel` is set to `gaussian`. The best value of *k* is chosen between 1 and `kmax` by leave-one-out. No outer cross-validation is needed.

7.6.3 Qbar, boosted trees algorithm

Algorithm $\widehat{\mathcal{A}}_{\bar{Q}, \text{trees}}$ is obtained by combining `estimate_Qbar` and `bstTree_algo`. The training of $\widehat{\mathcal{A}}_{\bar{Q}, \text{trees}}$ (i.e., the making of the output $\widehat{\mathcal{A}}_{\bar{Q}, \text{trees}}(P_n)$) is implemented based on function `caret::train` of the `caret` package. Some additional specifications are provided in `bstTree_grid` and `bstTree_control`.

In a nutshell, $\widehat{\mathcal{A}}_{\bar{Q}, \text{trees}}$ estimates $\bar{Q}_0(1, \cdot)$ and $\bar{Q}_0(0, \cdot)$ separately. Each of them is estimated by boosted trees as implemented in function `bst::bst` from the `bst` (gradient boosting) package (to see its man page, simply run `?bst::bst`).⁴ The following chunk of code trains algorithm $\widehat{\mathcal{A}}_{\bar{Q}, \text{trees}}$ on P_n , and reveals what are the optimal fine-tune parameters for the estimation of $\bar{Q}_0(1, \cdot)$ and $\bar{Q}_0(0, \cdot)$:

```
Qbar_hat_trees <- estimate_Qbar(head(obs, 1e3),
                               algorithm = bstTree_algo,
                               trControl = bstTree_control,
                               tuneGrid = bstTree_grid)

Qbar_hat_trees %>% filter(a == "one") %>% pull(fit) %>%
  capture.output %>% tail(3) %>% str_wrap(width = 60) %>% cat
#> RMSE was used to select the optimal model using the smallest
#> value. The final values used for the model were mstop = 30,
#> maxdepth = 1 and nu = 0.1.

Qbar_hat_trees %>% filter(a == "zero") %>% pull(fit) %>%
  capture.output %>% tail(3) %>% str_wrap(width = 60) %>% cat
#> RMSE was used to select the optimal model using the smallest
#> value. The final values used for the model were mstop = 20,
#> maxdepth = 1 and nu = 0.2.
```

We can compare visually the estimators $\bar{Q}_{n, \text{kNN}}$, $\bar{Q}_{n, \text{trees}} \doteq \widehat{\mathcal{A}}_{\bar{Q}, \text{trees}}(P_n)$ with its target \bar{Q}_0 , see Figure 7.3. In summary, $\bar{Q}_{n, \text{kNN}}$ is rather good, though very versatile at the vicinity of the break points. As for $\bar{Q}_{n, \text{trees}}$, it does not seem to capture the shape of its target.

```
fig %>%
  mutate(trees_1 = compute_Qbar_hatAW(1, w, Qbar_hat_trees),
         trees_0 = compute_Qbar_hatAW(0, w, Qbar_hat_trees)) %>%
  pivot_longer(-w, names_to = "f", values_to = "value") %>%
  extract(f, c("f", "a"), "([^\_]+)_([01]+)") %>%
  mutate(a = paste0("a=", a)) %>%
```

⁴Specifically, argument `mstop` (number of boosting iterations for prediction) is one among 10, 20 and 30; argument `nu` (stepsize of the shrinkage parameter) is one among 0.1 and 0.2; argument `maxdepth` (maximum depth of the base learner, a tree) is one among 1, 2 and 5. An outer 10-fold cross-validation is carried out to select the best combination of fine-tune parameters.

```
ggplot +
  geom_line(aes(x = w, y = value, color = f), size = 1) +
  labs(y = "f(w)",
       title = bquote("Visualizing" ~ bar(Q)[0] ~ "and its estimators")) +
  ylim(NA, 1) +
  facet_wrap(~ a)
```

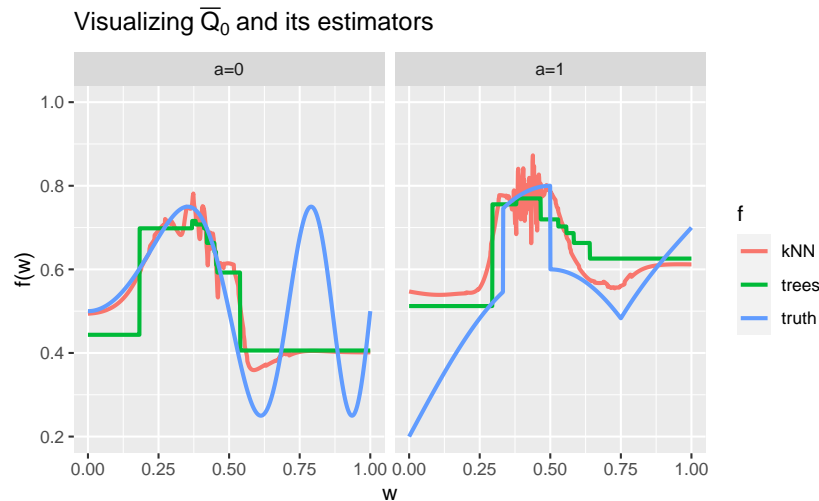


Figure 7.3: Comparing to their target two (machine learning-based) estimators of \bar{Q}_0 , one based on the k -nearest neighbors and the other on boosted trees.

7.7 \bar{Q} , machine learning-based algorithms

1. Using `estimate_Q`, make your own machine learning-based algorithm for the estimation of \bar{Q}_0 .
2. Train your algorithm on the same data set as $\hat{\mathcal{A}}_{\bar{Q}, \text{kNN}}$ and $\hat{\mathcal{A}}_{\bar{Q}, \text{trees}}$. If, like $\hat{\mathcal{A}}_{\bar{Q}, \text{trees}}$, your algorithm includes a fine-tuning procedure, comment upon the optimal, data-driven specification.
3. Plot your estimators of $\bar{Q}_0(1, \cdot)$ and $\bar{Q}_0(0, \cdot)$ on Figure 7.3.

Section 8

Two “naive” inference strategies

8.1 Why “naive”?

In this section, we present and discuss two strategies for the inference of $\Psi(P_0)$. In light of Section 7.1, both unfold in *two* stages. During the first stage, some features among $Q_{0,W}$, \bar{G}_0 and \bar{Q}_0 (the Ψ -specific nuisance parameters, see Section 7) are estimated. During the second stage, these estimators are used to build estimators of $\Psi(P_0)$.

Although the strategies sound well conceived, a theoretical analysis reveals that they lack a third stage trying to correct an inherent flaw. They are thus said *naïve*. The analysis and a first *modus operandi* are presented in Section 9.1.

8.2 IPTW estimator

8.2.1 Construction and computation

In Section 6.3, we developed an IPTW estimator, ψ_n^b , *assuming that* we knew \bar{G}_0 beforehand. What if we did not? Obviously, we could estimate it and substitute the estimator of $\ell\bar{G}_0$ for $\ell\bar{G}_0$ in (6.4).

Let $\widehat{\mathcal{A}}_{\bar{G}}$ be an algorithm designed for the estimation of \bar{G}_0 (see Section 7.4). We denote by $\bar{G}_n \doteq \widehat{\mathcal{A}}_{\bar{G}}(P_n)$ the output of the algorithm trained on P_n , and by $\ell\bar{G}_n$ the resulting (empirical) function given by

$$\ell\bar{G}_n(A, W) \doteq A\bar{G}_n(W) + (1 - A)(1 - \bar{G}_n(W)).$$

In light of (6.4), introduce

$$\psi_n^c \doteq \frac{1}{n} \sum_{i=1}^n \left(\frac{2A_i - 1}{\ell \bar{G}_n(A_i, W_i)} Y_i \right).$$

From a computational point of view, the `tlrider` package makes it easy to build ψ_n^c . Recall that

```
compute_iptw(head(obs, 1e3), Gbar)
```

implements the computation of ψ_n^b based on the $n = 1000$ first observations stored in `obs`, using the true feature \bar{G}_0 stored in `Gbar`, see Section 6.3.3 and the construction of `psi_hat_ab`. Similarly,

```
Gbar_hat <- estimate_Gbar(head(obs, 1e3), working_model_G_one)
compute_iptw(head(obs, 1e3), wrapper(Gbar_hat)) %>% pull(psi_n)
#> [1] 0.0915
```

implements (i) the estimation of \bar{G}_0 with $\bar{G}_n/\text{Gbar_hat}$ using algorithm $\widehat{\mathcal{A}}_{\bar{G},1}$ (first line) then (ii) the computation of ψ_n^c (second line), both based on the same observations as above.

Note how we use function `wrapper` (simply run `?wrapper` to see its man page).

8.2.2 Elementary statistical properties

Because \bar{G}_n minimizes the empirical risk over a finite-dimensional, identifiable, and **well-specified** working model, $\sqrt{n}(\psi_n^c - \psi_0)$ converges in law to a centered Gaussian law. Moreover, the asymptotic variance of $\sqrt{n}(\psi_n^c - \psi_0)$ is **conservatively**¹ estimated with

$$\begin{aligned} v_n^c &\doteq \text{Var}_{P_n} \left(\frac{2A - 1}{\ell \bar{G}_n(A, W)} Y \right) \\ &= \frac{1}{n} \sum_{i=1}^n \left(\frac{2A_i - 1}{\ell \bar{G}_n(A_i, W_i)} Y_i - \psi_n^c \right)^2. \end{aligned}$$

We investigate *empirically* the statistical behavior of ψ_n^c in Section 8.2.3. For an analysis of the reason why v_n^c is a conservative estimator of the asymptotic variance of $\sqrt{n}(\psi_n^c - \psi_0)$, see there in Appendix C.1.1.

Before proceeding, let us touch upon what would have happened if we had used a less amenable algorithm $\widehat{\mathcal{A}}_{\bar{G}}$. For instance, $\widehat{\mathcal{A}}_{\bar{G}}$ could still be well-specified² but so *versatile/complex* (as opposed to being based on well-behaved, finite-dimensional parametric

¹In words, v_n^c converges to an upper-bound of the true asymptotic variance.

²Well-specified *e.g.* in the sense that the target \bar{G}_0 of $\widehat{\mathcal{A}}_{\bar{G}}$ belongs to the closure of the algorithm's image $\widehat{\mathcal{A}}_{\bar{G}}(\mathcal{M}^{\text{empirical}})$ or, in other words, can be approximated arbitrarily well by an output of the algorithm.

model) that the estimator \bar{G}_n , though still consistent, would converge slowly to its target. Then, root- n consistency would fail to hold. Or $\widehat{\mathcal{A}}_{\bar{G}}$ could be mis-specified and there would be no guarantee at all that the resulting estimator ψ_n^c be even consistent.

8.2.3 Empirical investigation

Let us compute ψ_n^c on the same `iter = 1000` independent samples of independent observations drawn from P_0 as in Section 6.3. As explained in Sections 5 and 6.3.3, we first make `iter` data sets out of the `obs` data set (third line), then train algorithm $\widehat{\mathcal{A}}_{\bar{G},1}$ on each of them (fifth to seventh lines). After the first series of commands the object `learned_features_fixed_sample_size`, a `tibble`, contains 1000 rows and three columns.

We created `learned_features_fixed_sample_size` to store the estimators of \bar{G}_0 for future use. We will at a later stage enrich the object, for instance by adding to it estimators of \bar{Q}_0 obtained by training different algorithms on each smaller data set.

In the second series of commands, the object `psi_hat_abc` is obtained by adding to `psi_hat_ab` (see Section 6.3.3) an 1000 by four `tibble` containing notably the values of ψ_n^c and $\sqrt{v_n^c}/\sqrt{n}$ computed by calling `compute_iptw`. The object also contains the values of the recentered (with respect to ψ_0) and renormalized $\sqrt{n}/\sqrt{v_n^c}(\psi_n^c - \psi_0)$. Finally, `bias_abc` reports amounts of bias (at the renormalized scale).

```
learned_features_fixed_sample_size <-
  obs %>% as_tibble %>%
  mutate(id = (seq_len(n()) - 1) %% iter) %>%
  nest(obs = c(W, A, Y)) %>%
  mutate(Gbar_hat =
    map(obs,
      ~ estimate_Gbar(., algorithm = working_model_G_one)))

psi_hat_abc <-
  learned_features_fixed_sample_size %>%
  mutate(est_c =
    map2(obs, Gbar_hat,
      ~ compute_iptw(as.matrix(.x), wrapper(.y, FALSE)))) %>%
  unnest(est_c) %>% select(-Gbar_hat, -obs) %>%
  mutate(clt = (psi_n - psi_zero) / sig_n,
    type = "c") %>%
  full_join(psi_hat_ab)

(bias_abc <- psi_hat_abc %>%
  group_by(type) %>% summarise(bias = mean(clt)))
#> # A tibble: 3 x 2
```

```
#>   type      bias
#>   <chr>    <dbl>
#> 1 a       1.40
#> 2 b       0.0353
#> 3 c      -0.00443
```

By the above chunk of code, the average of $\sqrt{n/v_n^c}(\psi_n^c - \psi_0)$ computed across the realizations is equal to -0.004 (see `bias_abc`). In words, the average bias of ψ_n^c is of the same magnitude as that of ψ_n^b despite the fact that the construction of ψ_n^c hinges on the estimation of \bar{G}_0 (based on the well-specified algorithm $\hat{\mathcal{A}}_{\bar{G},1}$).

We represent the empirical laws of the recentered (with respect to ψ_0) and renormalized ψ_n^a , ψ_n^b and ψ_n^c in Figures 8.1 (kernel density estimators) and 8.2 (quantile-quantile plots).

```
fig_bias_ab +
  geom_density(aes(colt, fill = type, colour = type), psi_hat_abc, alpha = 0.1) +
  geom_vline(aes(xintercept = bias, colour = type),
             bias_abc, size = 1.5, alpha = 0.5) +
  xlim(-3, 4) +
  labs(y = "",
       x = bquote(paste(sqrt(n/v[n]^{list(a, b, c)}) *
                        (psi[n]^{list(a, b, c)} - psi[0]))))
```

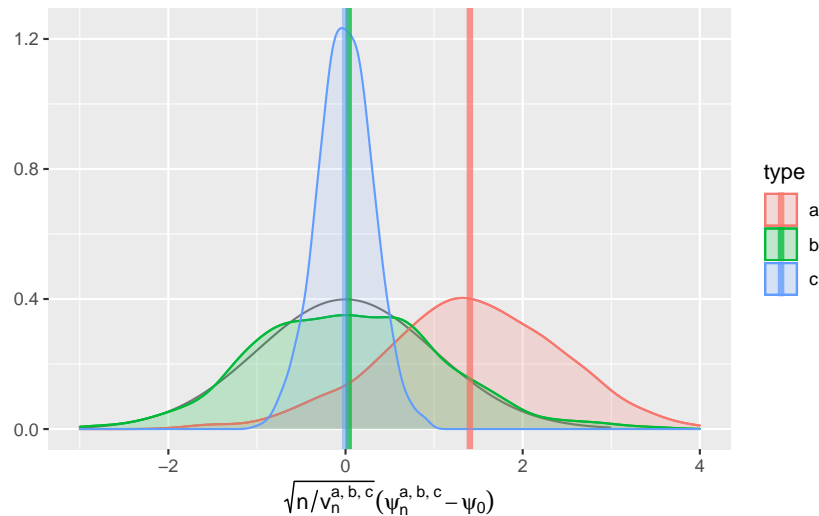


Figure 8.1: Kernel density estimators of the law of three estimators of ψ_0 (recentered with respect to ψ_0 , and renormalized), one of them misconceived (a), one assuming that \bar{G}_0 is known (b) and one that hinges on the estimation of \bar{G}_0 (c). The present figure includes Figure 6.1 (but the colors differ). Built based on `iter` independent realizations of each estimator.


```
ggplot(psi_hat_abc, aes(sample = clt, fill = type, colour = type)) +
  geom_abline(intercept = 0, slope = 1, alpha = 0.5) +
  geom_qq(alpha = 1)
```

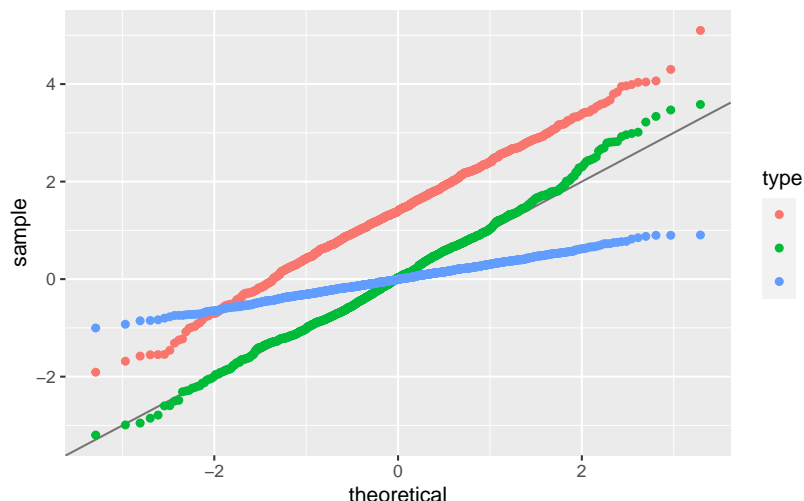


Figure 8.2: Quantile-quantile plot of the standard normal law against the empirical laws of three estimators of ψ_0 , one of them misconceived (a), one assuming that \bar{G}_0 is known (b) and one that hinges on the estimation of \bar{G}_0 (c). Built based on `iter` independent realizations of each estimator.

Figures 8.1 and 8.2 confirm that ψ_n^c behaves as well as ψ_n^b in terms of bias — but remember that we acted as oracles when we chose the well-specified algorithm $\widehat{\mathcal{A}}_{\bar{G},1}$. They also corroborate that v_n^c , the estimator of the asymptotic variance of $\sqrt{n}(\psi_n^c - \psi_0)$, is conservative: for instance, the corresponding bell-shaped blue curve is too much concentrated around its axis of symmetry.

The actual asymptotic variance of $\sqrt{n}(\psi_n^c - \psi_0)$ can be estimated with the empirical variance of the `iter` replications of the construction of ψ_n^c .

```
(emp_sig_n <- psi_hat_abc %>% filter(type == "c") %>%
  summarize(sd(psi_n)) %>% pull)
#> [1] 0.0175
(summ_sig_n <- psi_hat_abc %>% filter(type == "c") %>% select(sig_n) %>%
  summary)
#>      sig_n
#> Min.    :0.0523
#> 1st Qu.:0.0549
#> Median :0.0560
#> Mean    :0.0561
#> 3rd Qu.:0.0570
```

```
#> Max. :0.0631
```

The empirical standard deviation is approximately 3.213 times smaller than the average *estimated* standard deviation. The estimator is conservative indeed! Furthermore, note the better fit with the density of the standard normal density of the kernel density estimator of the law of $\sqrt{n}(\psi_n^c - \psi_0)$ **renormalized with emp_sig_n**.

```
clt_c <- psi_hat_abc %>% filter(type == "c") %>%
  mutate(clt = clt * sig_n / emp_sig_n)

fig_bias_ab +
  geom_density(aes(clt, fill = type, colour = type), clt_c, alpha = 0.1) +
  geom_vline(aes(xintercept = bias, colour = type),
             bias_abc, size = 1.5, alpha = 0.5) +
  xlim(-3, 4) +
  labs(y = "",
       x = bquote(paste(sqrt(n/v[n]^{list(a, b, c)}) *
                        (psi[n]^{list(a, b, c)} - psi[0]))))
```

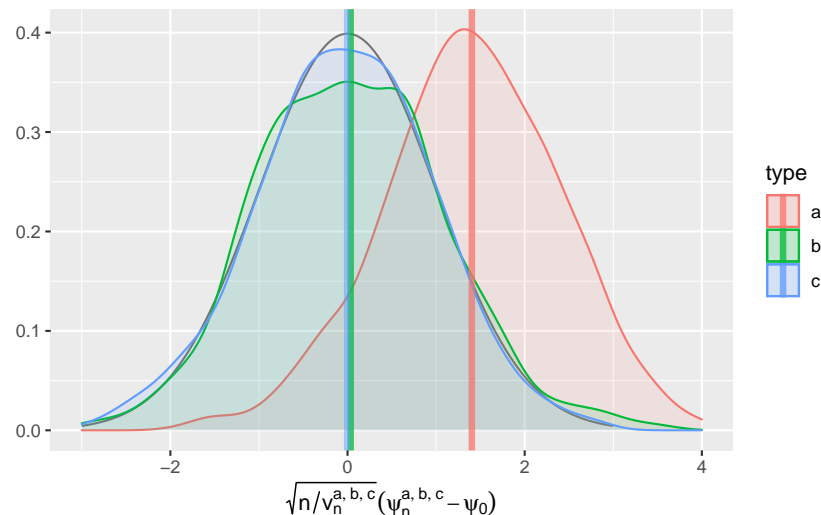


Figure 8.3: Kernel density estimators of the law of three estimators of ψ_0 (recentred with respect to ψ_0 , and renormalized), one of them misconceived (a), one assuming that \bar{G}_0 is known (b) and one that hinges on the estimation of \bar{G}_0 **and an estimator of the asymptotic variance computed across the replications** (c). The present figure includes Figure 6.1 (but the colors differ) and it should be compared to Figure 8.2. Built based on `iter` independent realizations of each estimator.

Workaround. In a real world data-analysis, one could correct the estimation of the asymptotic variance of $\sqrt{n}(\psi_n^c - \psi_0)$. We could for instance derive the influence function as it

is described there in Appendix C.1.1 and use the corresponding influence function-based estimator of the variance. One could also rely on the cross-validation, possibly combined with the previous workaround. Or one could also rely on the bootstrap.³ This, however, would only make sense if one knew for sure that the algorithm for the estimation of \tilde{G}_0 is well-specified.

8.3 ⚙ Investigating further the IPTW inference strategy

1. Building upon the chunks of code devoted to the repeated computation of ψ_n^b and its companion quantities, construct confidence intervals for ψ_0 of (asymptotic) level 95%, and check if the empirical coverage is satisfactory. Note that if the coverage was exactly 95%, then the number of confidence intervals that would contain ψ_0 would follow a binomial law with parameters `iter` and 0.95, and recall that function `binom.test` performs an exact test of a simple null hypothesis about the probability of success in a Bernoulli experiment against its three one-sided and two-sided alternatives.
2. Discuss what happens when the dimension of the (still well-specified) working model grows. Start with the built-in working model `working_model_G_two`. The following chunk of code re-defines `working_model_G_two`

```
## make sure '1/2' and '1' belong to 'powers'
powers <- rep(seq(1/4, 3, by = 1/4), each = 2)
working_model_G_two <- list(
  model = function(...) {trim_glm_fit(glm(family = binomial(), ...))},
  formula = stats::as.formula(
    paste("A ~",
          paste(c("I(W^", "I(abs(W - 5/12)^"),
                powers,
                sep = "", collapse = ") + "),
          ")")
  ),
  type_of_preds = "response"
)
attr(working_model_G_two, "ML") <- FALSE
```

3. Play around with argument `powers` (making sure that 1/2 and 1 belong to it), and plot graphics similar to those presented in Figures 8.1 and 8.2.
4. Discuss what happens when the working model is mis-specified. You could use the built-in working model `working_model_G_three`.

³That is, replicate the construction of ψ_n^c many times based on data sets obtained by resampling from the original data set, then estimate the asymptotic variance with the empirical variance of ψ_n^c computed across the replications.

5. Repeat the analysis developed in response to problem 1 above but for ψ_n^c . What can you say about the coverage of the confidence intervals?
6. 2 (Follow-up to problem 5). Implement the bootstrap procedure evoked at the end of Section 8.2.3. Repeat the analysis developed in response to problem 1. Compare your results with those to problem 5.
7. 2 Is it legitimate to infer the asymptotic variance of ψ_n^c with v_n^c when one relies on a very data-adaptive/versatile algorithm to estimate \bar{G}_0 ?

8.4 G-computation estimator

8.4.1 Construction and computation

Let $\widehat{\mathcal{A}}_{Q_W}$ be an algorithm designed for the estimation of $Q_{0,W}$ (see Section 7.3). We denote by $Q_{n,W} \doteq \widehat{\mathcal{A}}_{Q_W}(P_n)$ the output of the algorithm trained on P_n .

Let $\widehat{\mathcal{A}}_{\bar{Q}}$ be an algorithm designed for the estimation of \bar{Q}_0 (see Section 7.6). We denote by $\bar{Q}_n \doteq \widehat{\mathcal{A}}_{\bar{Q}}(P_n)$ the output of the algorithm trained on P_n .

Equation (2.1) suggests the following, simple estimator of $\Psi(P_0)$:

$$\psi_n \doteq \int (\bar{Q}_n(1, w) - \bar{Q}_n(0, w)) dQ_{n,W}(w). \quad (8.1)$$

In words, this estimator is implemented by first regressing Y on (A, W) , then by marginalizing with respect to the estimated law of W . The resulting estimator is referred to as a *G-computation* (or *standardization*) estimator.

From a computational point of view, the `tlrider` package makes it easy to build the G-computation estimator. Recall that we have already estimated the marginal law $Q_{0,W}$ of W under P_0 by training the algorithm $\widehat{\mathcal{A}}_{Q_W}$ as it is implemented in `estimate_QW` on the $n = 1000$ first observations in `obs` (see Section 7.3):

```
QW_hat <- estimate_QW(head(obs, 1e3))
```

Recall that $\widehat{\mathcal{A}}_{\bar{Q},1}$ is the algorithm for the estimation of \bar{Q}_0 as it is implemented in `estimate_Qbar` with its argument `algorithm` set to the built-in `working_model_Q_one` (see Section 7.5). Recall also that $\widehat{\mathcal{A}}_{\bar{Q},\text{kNN}}$ is the algorithm for the estimation of \bar{Q}_0 as it is implemented in `estimate_Qbar` with its argument `algorithm` set to the built-in `kknn_algo` (see Section 7.6.2). We have already trained the latter on the $n = 1000$ first observations in `obs`. Let us train the former on the same data set:

```
Qbar_hat_kknn <- estimate_Qbar(head(obs, 1e3),
                               algorithm = kknn_algo,
```

```
trControl = kknn_control,
tuneGrid = kknn_grid)
```

```
Qbar_hat_d <- estimate_Qbar(head(obs, 1e3), working_model_Q_one)
```

With these estimators handy, computing the G-computation estimator is as simple as running the following chunk of code:

```
(compute_gcomp(QW_hat, wrapper(Qbar_hat_kknn, FALSE), 1e3))
#> # A tibble: 1 x 2
#>   psi_n sig_n
#>   <dbl> <dbl>
#> 1 0.0887 0.00245
(compute_gcomp(QW_hat, wrapper(Qbar_hat_d, FALSE), 1e3))
#> # A tibble: 1 x 2
#>   psi_n sig_n
#>   <dbl> <dbl>
#> 1 0.0961 0.00161
```

Note how we use function `wrapper` again, and that it is necessary to provide the number of observations upon which the estimation of the Q_W and \bar{Q} features of P_0 .

8.4.2 Elementary statistical properties

This subsection is very similar to its counterpart for the IPTW estimator, see Section 8.2.2.

Let us denote by $\bar{Q}_{n,1}$ the output of algorithm $\widehat{\mathcal{A}}_{\bar{Q},1}$ trained on P_n , and recall that $\bar{Q}_{n,\text{KNN}}$ is the output of algorithm $\widehat{\mathcal{A}}_{\bar{Q},\text{KNN}}$ trained on P_n . Let ψ_n^d and ψ_n^e be the G-computation estimators obtained by substituting $\bar{Q}_{n,1}$ and $\bar{Q}_{n,\text{KNN}}$ for \bar{Q}_n in (8.1), respectively.

If $\bar{Q}_{n,\bullet}$ minimized the empirical risk over a finite-dimensional, identifiable, and **well-specified** working model, then $\sqrt{n}(\psi_n^\bullet - \psi_0)$ would converge in law to a centered Gaussian law (here ψ_n^\bullet represents the G-computation estimator obtained by substituting $\bar{Q}_{n,\bullet}$ for \bar{Q}_n in (8.1)). Moreover, the asymptotic variance of $\sqrt{n}(\psi_n^\bullet - \psi_0)$ would be estimated **anti-conservatively**⁴ with

$$v_n^d \doteq \text{Var}_{P_n} (\bar{Q}_{n,1}(1, \cdot) - \bar{Q}_{n,1}(0, \cdot)) \quad (8.2)$$

$$= \frac{1}{n} \sum_{i=1}^n (\bar{Q}_{n,1}(1, W_i) - \bar{Q}_{n,1}(0, W_i) - \psi_n^d)^2. \quad (8.3)$$

⁴In words, v_n^d converges to a lower-bound of the true asymptotic variance.

Unfortunately, algorithm $\widehat{\mathcal{A}}_{\bar{Q},1}$ is mis-specified and $\widehat{\mathcal{A}}_{\bar{Q},\text{kNN}}$ is not based on a finite-dimensional working model. Nevertheless, function `compute_gcomp` estimates (in general, very poorly) the asymptotic variance with (8.3).

We investigate *empirically* the statistical behavior of ψ_n^d in Section 8.4.3. For an analysis of the reason why v_n^d is an anti-conservative estimator of the asymptotic variance of $\sqrt{n}(\psi_n^d - \psi_0)$, see there in Appendix C.1.2. We wish to emphasize that anti-conservativeness is even more embarrassing than conservativeness (both being contingent on the fact that the algorithms are well-specified, fact that cannot be true in the present case in real world situations).

What would happen if we used a less amenable algorithm $\widehat{\mathcal{A}}_{\bar{Q}}$. For instance, $\widehat{\mathcal{A}}_{\bar{Q}}$ could still be well-specified but so *versatile/complex* (as opposed to being based on well-behaved, finite-dimensional parametric model) that the estimator \bar{Q}_n , though still consistent, would converge slowly to its target. Then, root- n consistency would fail to hold. We can explore empirically this situation with estimator ψ_n^e that hinges on algorithm $\widehat{\mathcal{A}}_{\bar{Q},\text{kNN}}$. Or $\widehat{\mathcal{A}}_{\bar{Q}}$ could be mis-specified and there would be no guarantee at all that the resulting estimator ψ_n be even consistent.

8.4.3 Empirical investigation, fixed sample size

Let us compute ψ_n^d and ψ_n^e on the same `iter = 1000` independent samples of independent observations drawn from P_0 as in Sections 6.3 and 8.2.3. We first enrich object `learned_features_fixed_sample_size` that was created in Section 8.2.3, adding to it estimators of \bar{Q}_0 obtained by training algorithms $\widehat{\mathcal{A}}_{\bar{Q},1}$ and $\widehat{\mathcal{A}}_{\bar{Q},\text{kNN}}$ on each smaller data set.

The second series of commands creates object `psi_hat_de`, an 1000 by six `tibble` containing notably the values of ψ_n^d and $\sqrt{v_n^d}/\sqrt{n}$ computed by calling `compute_gcomp`, and those of the recentered (with respect to ψ_0) and renormalized $\sqrt{n}/\sqrt{v_n^d}(\psi_n^d - \psi_0)$. Because we know beforehand that v_n^d under-estimates the actual asymptotic variance of $\sqrt{n}(\psi_n^d - \psi_0)$, the `tibble` also includes the values of $\sqrt{n}/\sqrt{v^{d*}}(\psi_n^d - \psi_0)$ where the estimator v^{d*} of the asymptotic variance is computed *across the replications of ψ_n^d* . The `tibble` includes the same quantities pertaining to ψ_n^e , although there is no theoretical guarantee that the central limit theorem does hold and, even if it did, that the counterpart v_n^e to v_n^d estimates in any way the asymptotic variance of $\sqrt{n}(\psi_n^e - \psi_0)$.

Finally, `bias_de` reports amounts of bias (at the renormalized scales — plural). There is one value of bias for each combination of (i) type of the estimator (d or e) and (ii) how the renormalization is carried out, either based on v_n^d and v_n^e (`auto_renormalization` is `TRUE`) or on the estimator of the asymptotic variance computed across the replications of ψ_n^d and ψ_n^e (`auto_renormalization` is `FALSE`).

```
learned_features_fixed_sample_size <-  
  learned_features_fixed_sample_size %>%
```

```

mutate(Qbar_hat_d =
  map(obs,
    ~ estimate_Qbar(., algorithm = working_model_Q_one)),
  Qbar_hat_e =
    map(obs,
      ~ estimate_Qbar(., algorithm = kknn_algo,
        trControl = kknn_control,
        tuneGrid = kknn_grid))) %>%
mutate(QW = map(obs, estimate_QW),
  est_d =
    pmap(list(QW, Qbar_hat_d, n()),
      ~ compute_gcomp(..1, wrapper(..2, FALSE), ..3)),
  est_e =
    pmap(list(QW, Qbar_hat_e, n()),
      ~ compute_gcomp(..1, wrapper(..2, FALSE), ..3)))

psi_hat_de <- learned_features_fixed_sample_size %>%
  select(est_d, est_e) %>%
  pivot_longer(c(`est_d`, `est_e`),
    names_to = "type", values_to = "estimates") %>%
  extract(type, "type", "_(.[de])$") %>%
  unnest(estimates) %>%
  group_by(type) %>%
  mutate(sig_alt = sd(psi_n)) %>%
  mutate(clt_ = (psi_n - psi_zero) / sig_n,
    clt_alt = (psi_n - psi_zero) / sig_alt) %>%
  pivot_longer(c(`clt_`, `clt_alt`),
    names_to = "key", values_to = "clt") %>%
  extract(key, "key", "_(.*)$") %>%
  mutate(key = ifelse(key == "", TRUE, FALSE)) %>%
  rename("auto_renormalization" = key)

(bias_de <- psi_hat_de %>%
  group_by(type, auto_renormalization) %>%
  summarize(bias = mean(clt)) %>% ungroup)

#> # A tibble: 4 x 3
#>   type auto_renormalization bias
#>   <chr> <lgl>               <dbl>
#> 1 d     FALSE                0.240
#> 2 d     TRUE                 2.25
#> 3 e     FALSE                0.122
#> 4 e     TRUE                 0.679

```

```

fig <- ggplot() +
  geom_line(aes(x = x, y = y),
    data = tibble(x = seq(-4, 4, length.out = 1e3),
      y = dnorm(x)),
    linetype = 1, alpha = 0.5) +
  geom_density(aes(colt, fill = type, colour = type),
    psi_hat_de, alpha = 0.1) +
  geom_vline(aes(xintercept = bias, colour = type),
    bias_de, size = 1.5, alpha = 0.5) +
  facet_wrap(~ auto_renormalization,
    labeller =
      as_labeller(c(`TRUE` = "auto-renormalization: TRUE",
        `FALSE` = "auto-renormalization: FALSE")),
    scales = "free")

fig +
  labs(y = "",
    x = bquote(paste(sqrt(n/v[n]^{list(d, e)}) *
      (psi[n]^{list(d, e)} - psi[0]))))

```

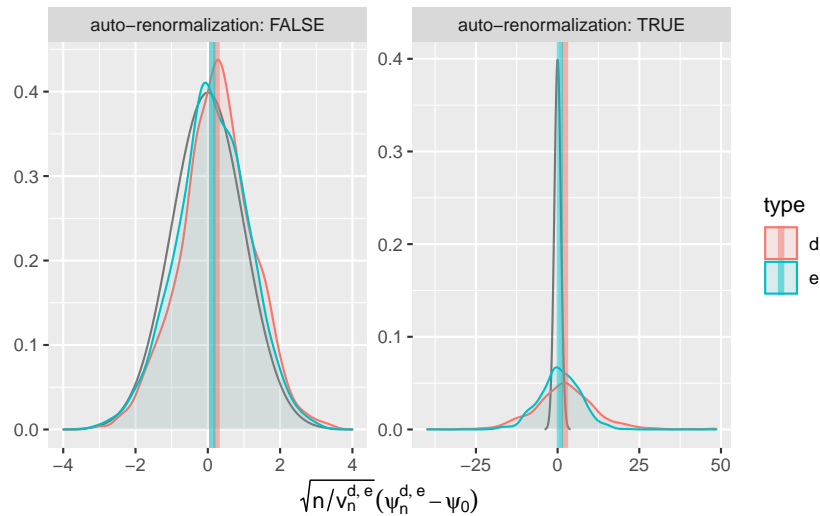


Figure 8.4: Kernel density estimators of the law of two G-computation estimators of ψ_0 (recentred with respect to ψ_0 , and renormalized). The estimators respectively hinge on algorithms $\hat{\mathcal{A}}_{\bar{Q},1}$ (d) and $\hat{\mathcal{A}}_{\bar{Q},\text{kNN}}$ (e) to estimate \bar{Q}_0 . Two renormalization schemes are considered, either based on an estimator of the asymptotic variance (right) or on the empirical variance computed across the `iter` independent replications of the estimators (left). We emphasize that the x -axis ranges differ starkly between the left and right plots.

We represent the empirical laws of the recentered (with respect to ψ_0) and renormalized ψ_n^d and ψ_n^e in Figure 8.4 (kernel density estimators). Two renormalization schemes are considered, either based on an estimator of the asymptotic variance (left) or on the empirical variance computed across the `iter` independent replications of the estimators (right). We emphasize that the x -axis ranges differ starkly between the left and right plots.

Two important comments are in order. First, on the one hand, the G-computation estimator ψ_n^d is biased. Specifically, by the above chunk of code, the averages of $\sqrt{n/v_n^d}(\psi_n^d - \psi_0)$ and $\sqrt{n/v_n^{d*}}(\psi_n^d - \psi_0)$ computed across the realizations are equal to 2.247 and 0.24 (see `bias_de`). On the other hand, the G-computation estimator ψ_n^e is biased too, though slightly less than ψ_n^d . Specifically, by the above chunk of code, the averages of $\sqrt{n/v_n^e}(\psi_n^e - \psi_0)$ and $\sqrt{n/v_n^{e*}}(\psi_n^e - \psi_0)$ computed across the realizations are equal to 0.679 and 0.122 (see `bias_de`). We can provide an oracular explanation. Estimator ψ_n^d suffers from the poor approximation of \bar{Q}_0 by $\hat{\mathcal{A}}_{\bar{Q},1}(P_n)$, a result of the algorithm's mis-specification. As for ψ_n^e , it behaves better because $\hat{\mathcal{A}}_{\bar{Q},\text{kNN}}(P_n)$ approximates \bar{Q}_0 better than $\hat{\mathcal{A}}_{\bar{Q},1}(P_n)$, an apparent consequence of the greater versatility of the algorithm.

Second, we get a visual confirmation that v_n^d under-estimates the actual asymptotic variance of $\sqrt{n}(\psi_n^d - \psi_0)$: the right-hand side red bell-shaped curve is too dispersed. In contrast, the right-hand side blue bell-shaped curve is much closer to the black curve that represents the density of the standard normal law. Looking at the left-hand side plot reveals that the empirical law of $\sqrt{n/v_n^{d*}}(\psi_n^d - \psi_0)$, once translated to compensate for the bias, is rather close to the black curve. This means that the random variable is approximately distributed like a Gaussian random variable. On the contrary, the empirical law of $\sqrt{n/v_n^e}(\psi_n^e - \psi_0)$ does not strike us as being as closely Gaussian-like as that of $\sqrt{n/v_n^{d*}}(\psi_n^d - \psi_0)$. By being more data-adaptive than $\hat{\mathcal{A}}_{\bar{Q},1}$, algorithm $\hat{\mathcal{A}}_{\bar{Q},\text{kNN}}$ yields a better estimator of \bar{Q}_0 . However, the rate of convergence of $\hat{\mathcal{A}}_{\bar{Q},\text{kNN}}(P_n)$ to its limit may be slower than root- n , invalidating a central limit theorem.

How do the estimated variances of ψ_n^d and ψ_n^e compare with their empirical counterparts (computed across the `iter` replications of the construction of the two estimators)?

```
## psi_n^d
(psi_hat_de %>% ungroup %>%
  filter(type == "d" & auto_renormalization) %>% pull(sig_n) %>% summary)
#>   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
#> 0.00061 0.00171 0.00208 0.00208 0.00244 0.00373
## psi_n^e
(psi_hat_de %>% ungroup %>%
  filter(type == "e" & auto_renormalization) %>% pull(sig_n) %>% summary)
#>   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
#> 0.00151 0.00261 0.00288 0.00289 0.00316 0.00430
```

The empirical standard deviation of ψ_n^d is approximately 8.56 times larger than the average

estimated standard deviation. The estimator is anti-conservative indeed!

As for the empirical standard deviation of ψ_n^e , it is approximately 6.093 times larger than the average *estimated* standard deviation.

8.4.4 2 Empirical investigation, varying sample size

```
sample_size <- c(5e3, 15e3)
block_size <- sum(sample_size)

learned_features_varying_sample_size <- obs %>% as_tibble %>%
  head(n = (nrow(.) %/% block_size) * block_size) %>%
  mutate(block = label(1:nrow(.), sample_size)) %>%
  nest(obs = c(W, A, Y))
```

First, we cut the data set into independent sub-data sets of sample size n in $\{5000, 1.5 \times 10^4\}$. Second, we infer ψ_0 as shown two chunks earlier. We thus obtain 50 independent realizations of each estimator derived on data sets of 2, increasing sample sizes.

```
learned_features_varying_sample_size <-
  learned_features_varying_sample_size %>%
  mutate(Qbar_hat_d =
    map(obs,
      ~ estimate_Qbar(., algorithm = working_model_Q_one)),
    Qbar_hat_e =
    map(obs,
      ~ estimate_Qbar(., algorithm = kknn_algo,
        trControl = kknn_control,
        tuneGrid = kknn_grid))) %>%
  mutate(QW = map(obs, estimate_QW),
    est_d =
    pmap(list(QW, Qbar_hat_d, n()),
      ~ compute_gcomp(..1, wrapper(..2, FALSE), ..3)),
    est_e =
    pmap(list(QW, Qbar_hat_e, n()),
      ~ compute_gcomp(..1, wrapper(..2, FALSE), ..3)))

root_n_bias <- learned_features_varying_sample_size %>%
  mutate(block = unlist(map(strsplit(block, "_"), ~.x[2])),
    sample_size = sample_size[as.integer(block)]) %>%
  select(block, sample_size, est_d, est_e) %>%
  pivot_longer(c(`est_d`, `est_e`),
```

```

      names_to = "type", values_to = "estimates") %>%
extract(type, "type", "_([de])$") %>%
unnest(estimates) %>%
group_by(block, type) %>%
mutate(sig_alt = sd(psi_n)) %>%
mutate(clt_ = (psi_n - psi_zero) / sig_n,
      clt_alt = (psi_n - psi_zero) / sig_alt) %>%
pivot_longer(c(`clt_`, `clt_alt`),
      names_to = "key", values_to = "clt") %>%
extract(key, "key", "_(.*)$") %>%
mutate(key = ifelse(key == "", TRUE, FALSE)) %>%
rename("auto_renormalization" = key)

```

The tibble called `root_n_bias` reports root- n times bias for all combinations of estimator and sample size. The next chunk of code presents visually our findings, see Figure 8.5. Note how we include the realizations of the estimators derived earlier and contained in `psi_hat_de` (thus breaking the independence between components of `root_n_bias`, a small price to pay in this context).

```

root_n_bias <- learned_features_fixed_sample_size %>%
  mutate(block = "0",
        sample_size = B/iter) %>% # because *fixed* sample size
  select(block, sample_size, est_d, est_e) %>%
  pivot_longer(c(`est_d`, `est_e`),
    names_to = "type", values_to = "estimates") %>%
  extract(type, "type", "_([de])$") %>%
  unnest(estimates) %>%
  group_by(block, type) %>%
  mutate(sig_alt = sd(psi_n)) %>%
  mutate(clt_ = (psi_n - psi_zero) / sig_n,
        clt_alt = (psi_n - psi_zero) / sig_alt) %>%
  pivot_longer(c(`clt_`, `clt_alt`),
    names_to = "key", values_to = "clt") %>%
  extract(key, "key", "_(.*)$") %>%
  mutate(key = ifelse(key == "", TRUE, FALSE)) %>%
  rename("auto_renormalization" = key) %>%
  full_join(root_n_bias)

root_n_bias %>% filter(auto_renormalization) %>%
  mutate(rnb = sqrt(sample_size) * (psi_n - psi_zero)) %>%
  group_by(sample_size, type) %>%
  ggplot() +
  stat_summary(aes(x = sample_size, y = rnb,

```

```

      group = interaction(sample_size, type),
      color = type),
    fun.data = mean_se, fun.args = list(mult = 1),
    position = position_dodge(width = 250), cex = 1) +
  stat_summary(aes(x = sample_size, y = rnb,
    group = interaction(sample_size, type),
    color = type),
    fun.data = mean_se, fun.args = list(mult = 1),
    position = position_dodge(width = 250), cex = 1,
    geom = "errorbar", width = 750) +
  stat_summary(aes(x = sample_size, y = rnb,
    color = type),
    fun = mean,
    position = position_dodge(width = 250),
    geom = "polygon", fill = NA) +
  geom_point(aes(x = sample_size, y = rnb,
    group = interaction(sample_size, type),
    color = type),
    position = position_dodge(width = 250),
    alpha = 0.1) +
  scale_x_continuous(breaks = unique(c(B / iter, sample_size))) +
  labs(x = "sample size n",
    y = bquote(paste(sqrt(n) * (psi[n]^{list(d, e)} - psi[0]))))

```

Root- n bias for ψ_n^d (red lines and points) is positive and tends to increase from sample size 1000 to 5000 and from 5000 to 1.5×10^4 . Moreover, root- n bias tends to be larger for ψ_n^d than for ψ_n^e . In addition, root- n bias for ψ_n^e tends to increase from sample size 1000 to 1.5×10^4 , where it tends to be positive too.⁵

In essence, we observe that the bias does not vanish faster than root- n . For ψ_n^d , this is because $\widehat{\mathcal{A}}_{\widehat{Q},1}$ is mis-specified and we expect that the bias increases at rate root- n . For ψ_n^e , this is because the estimator produced by the versatile $\widehat{\mathcal{A}}_{\widehat{Q},\text{kNN}}$ converges slowly to its limit. Can anything be done to amend ψ_n^d and ψ_n^e ?

8.5 Investigating further the G-computation estimation strategy

1. Implement the G-computation estimator based on well-specified working model. To do so, (i) create a copy `working_model_Q_two` of `working_model_Q_one`, (ii) replace

⁵We use the expression “tend to” because controlling for multiple testing makes it impossible to make a firm statement.

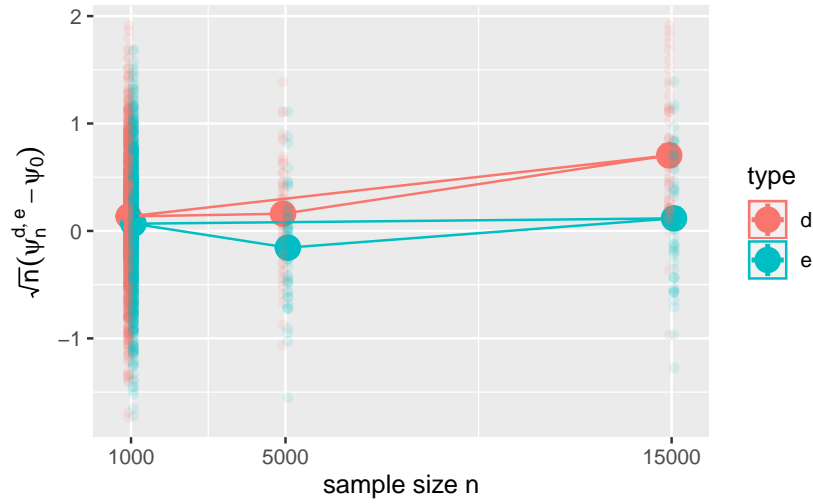


Figure 8.5: Evolution of root- n times bias versus sample size for two G-computation estimators of ψ_0 . The estimators respectively hinge on algorithms $\hat{\mathcal{A}}_{\bar{Q},1}$ (d) and $\hat{\mathcal{A}}_{\bar{Q},\text{kNN}}$ (e) to estimate \bar{Q}_0 . Big dots represent the average biases and vertical lines represent twice the standard error.

its **family** entry in such a way that \bar{Q}_0 falls in the corresponding working model, and (iii) adapt the chunk of code where we computed `Qbar_hat_d` in Section 8.4.1.

2. Evaluate the empirical properties of the estimator of problem 1.
3. Create a function to estimate the marginal law $Q_{0,W}$ of W by maximum likelihood estimation based on a mis-specified model that assumes (wrongly) that W is drawn from a Gaussian law with unknown mean and variance.
4. 2 Implement the G-computation estimator using either `working_model_Q_one` or `working_model_Q_two` and the estimator of $Q_{0,W}$ of problem 3.

Section 9

One-step correction

9.1 2 General analysis of plug-in estimators

Recall that $\widehat{\mathcal{A}}_{Q_W}$ is an algorithm designed for the estimation of $Q_{0,W}$ (see Section 7.3) and that we denote by $Q_{n,W} \doteq \widehat{\mathcal{A}}_{Q_W}(P_n)$ the output of the algorithm trained on P_n . Likewise, $\widehat{\mathcal{A}}_{\bar{G}}$ and $\widehat{\mathcal{A}}_{\bar{Q}}$ are two generic algorithms designed for the estimation of \bar{G}_0 and of \bar{Q}_0 (see Sections 7.4 and 7.6), $\bar{G}_n \doteq \widehat{\mathcal{A}}_{\bar{G}}(P_n)$ and $\bar{Q}_n \doteq \widehat{\mathcal{A}}_{\bar{Q}}(P_n)$ are their outputs once trained on P_n .

Let us now introduce P_n° a law in \mathcal{M} such that the Q_W , \bar{G} and \bar{Q} features of P_n° equal $Q_{n,W}$, \bar{G}_n and \bar{Q}_n , respectively. We say that any such law is *compatible* with $Q_{n,W}$, \bar{G}_n and \bar{Q}_n .

Now, let us substitute P_n° for P in (4.1):

$$\Psi(P_n^\circ) - \Psi(P_0) = -P_0 D^*(P_n^\circ) + \text{Rem}_{P_0}(P_n^\circ). \quad (9.1)$$

We show there in Appendix C.2 that, under conditions on the complexity/versatility of algorithms $\widehat{\mathcal{A}}_{\bar{G}}$ and $\widehat{\mathcal{A}}_{\bar{Q}}$ (often referred to as *regularity conditions*) and assuming that their outputs \bar{G}_n and \bar{Q}_n both consistently estimate their targets \bar{G}_0 and \bar{Q}_0 , it holds that

$$\begin{aligned} \Psi(P_n^\circ) - \Psi(P_0) &= -P_n D^*(P_n^\circ) + P_n D^*(P_0) + o_{P_0}(1/\sqrt{n}) \\ &= -P_n D^*(P_n^\circ) + \frac{1}{n} \sum_{i=1}^n D^*(P_0)(O_i) + o_{P_0}(1/\sqrt{n}). \end{aligned} \quad (9.2)$$

In light of (3.8), $\Psi(P_n^\circ)$ would be asymptotically linear with influence curve $\text{IC} = D^*(P_0)$ in the absence of the random term $-P_n D^*(P_n^\circ)$. Unfortunately, it turns out that this term can degrade dramatically the behavior of the plug-in estimator $\Psi(P_n^\circ)$.

9.2 One-step correction

Luckily, a *very simple workaround* allows to circumvent the problem. Proposed in [Le Cam, 1969] (see also [Pfanzagl, 1982] and [van der Vaart, 1998]), the workaround merely consists in subtracting the random term to the initial estimator, that is, in estimating $\Psi(P_0)$ not with $\Psi(P_n^\circ)$ but instead with

$$\psi_n^{\text{os}} \doteq \Psi(P_n^\circ) + P_n D^*(P_n^\circ) = \Psi(P_n^\circ) + \frac{1}{n} \sum_{i=1}^n D^*(P_n^\circ)(O_i). \quad (9.3)$$

Obviously, in light of (9.2), ψ_n^{os} is asymptotically linear with influence curve $\text{IC} = D^*(P_0)$. Thus, by the central limit theorem, $\sqrt{n}(\psi_n^{\text{os}} - \Psi(P_0))$ converges in law to a centered Gaussian distribution with variance

$$\text{Var}_{P_0}(D^*(P_0)(O)) = \text{E}_{P_0}(D^*(P_0)(O)). \quad (9.4)$$

The detailed general analysis of plug-in estimators developed there in Appendix C.2 also revealed that the above asymptotic variance is consistently estimated with

$$P_n D^*(P_n^\circ)^2 = \frac{1}{n} \sum_{i=1}^n D^*(P_n^\circ)^2(O_i). \quad (9.5)$$

Therefore, by the central limit theorem and Slutsky's lemma (see the argument there in Appendix B.3.1),

$$\left[\psi_n^{\text{os}} \pm \Phi^{-1}(1 - \alpha) \frac{P_n D^*(P_n^\circ)^2}{\sqrt{n}} \right]$$

is a confidence interval for $\Psi(P_0)$ with asymptotic level $(1 - 2\alpha)$.

9.3 Empirical investigation

In light of (9.3) if the estimator equals $\Psi(P_n^\circ)$, then performing a one-step correction essentially boils down to computing two quantities, $-P_n D^*(P_n^\circ)$ (the bias term) and $P_n D^*(P_n^\circ)^2$ (an estimator of the asymptotic variance of ψ_n^{os}). The `tlrider` package makes the operation very easy thanks to the function `apply_one_step_correction`.

Let us illustrate its use by updating the G-computation estimator built on the $n = 1000$ first observations in `obs` by relying on $\widehat{\mathcal{A}}_{\bar{Q}, \text{kNN}}$, that is, on the algorithm for the estimation of \bar{Q}_0 as it is implemented in `estimate_Qbar` with its argument `algorithm` set to the built-in `kknn_algo` (see Section 7.6.2). The algorithm has been trained earlier on this data set and produced the object `Qbar_hat_kknn`. The following chunk of code re-computes the corresponding G-computation estimator, using again the estimator `QW_hat` of the marginal law of W under P_0 (see Section 7.3), then applied the one-step correction:


```

(psin_kknn <- compute_gcomp(QW_hat, wrapper(Qbar_hat_kknn, FALSE), 1e3))
#> # A tibble: 1 x 2
#>   psi_n sig_n
#>   <dbl> <dbl>
#> 1 0.0887 0.00245
(psin_kknn_os <- apply_one_step_correction(head(obs, 1e3),
                                           wrapper(Gbar_hat, FALSE),
                                           wrapper(Qbar_hat_kknn, FALSE),
                                           psin_kknn$psi_n))

#> # A tibble: 1 x 3
#>   psi_n sig_n crit_n
#>   <dbl> <dbl>   <dbl>
#> 1 0.0888 0.0162 0.000124

```

In the call to `apply_one_step_correction` we provide (i) the data set at hand (first line), (ii) the estimator `Gbar_hat` of \bar{G}_0 that we built earlier by using algorithm $\hat{\mathcal{A}}_{\bar{G},1}$ (second line; see Section 7.4.2), (iii) the estimator `Qbar_hat_kknn` of \bar{Q}_0 and the G-computation estimator `psin_kknn` that resulted from it (third and fourth lines).

To assess what is the impact of the one-step correction, let us apply the one-step correction to the estimators that we built in Section 8.4.3. The object `learned_features_fixed_sample_size` already contains the estimated features of P_0 that are needed to perform the one-step correction to the estimators ψ_n^d and ψ_n^e , namely, thus we merely have to call the function `apply_one_step_correction`.

```

psi_hat_de_one_step <- learned_features_fixed_sample_size %>%
  mutate(os_est_d =
    pmap(list(obs, Gbar_hat, Qbar_hat_d, est_d),
          ~ apply_one_step_correction(as.matrix(..1),
                                     wrapper(..2, FALSE),
                                     wrapper(..3, FALSE),
                                     ..4$psi_n)),
    os_est_e =
    pmap(list(obs, Gbar_hat, Qbar_hat_e, est_e),
          ~ apply_one_step_correction(as.matrix(..1),
                                     wrapper(..2, FALSE),
                                     wrapper(..3, FALSE),
                                     ..4$psi_n))) %>%
  select(os_est_d, os_est_e) %>%
  pivot_longer(c(`os_est_d`, `os_est_e`),
               names_to = "type", values_to = "estimates") %>%
  extract(type, "type", "_(de)$") %>%
  mutate(type = paste0(type, "_one_step")) %>%

```

```

unnest(estimates) %>%
group_by(type) %>%
mutate(sig_alt = sd(psi_n)) %>%
mutate(clt_ = (psi_n - psi_zero) / sig_n,
       clt_alt = (psi_n - psi_zero) / sig_alt) %>%
pivot_longer(c(`clt_`, `clt_alt`),
             names_to = "key", values_to = "clt") %>%
extract(key, "key", "_(.*)$") %>%
mutate(key = ifelse(key == "", TRUE, FALSE)) %>%
rename("auto_renormalization" = key)

(bias_de_one_step <- psi_hat_de_one_step %>%
  group_by(type, auto_renormalization) %>%
  summarize(bias = mean(clt)) %>% ungroup)
#> # A tibble: 4 x 3
#>   type      auto_renormalization      bias
#>   <chr>      <lgl>                  <dbl>
#> 1 d_one_step FALSE                  -0.00668
#> 2 d_one_step TRUE                   -0.0240
#> 3 e_one_step FALSE                   0.0333
#> 4 e_one_step TRUE                    0.0171

fig <- ggplot() +
  geom_line(aes(x = x, y = y),
            data = tibble(x = seq(-4, 4, length.out = 1e3),
                          y = dnorm(x)),
            linetype = 1, alpha = 0.5) +
  geom_density(aes(clt, fill = type, colour = type),
               psi_hat_de_one_step, alpha = 0.1) +
  geom_vline(aes(xintercept = bias, colour = type),
             bias_de_one_step, size = 1.5, alpha = 0.5) +
  facet_wrap(~ auto_renormalization,
            labeller =
              as_labeller(c(`TRUE` = "auto-renormalization: TRUE",
                             `FALSE` = "auto-renormalization: FALSE")),
            scales = "free")

fig +
  labs(y = "",
       x = bquote(paste(sqrt(n/v[n]^{list(d, e, os)}) *
                      (psi[n]^{list(d, e, os)} - psi[0]))))

```

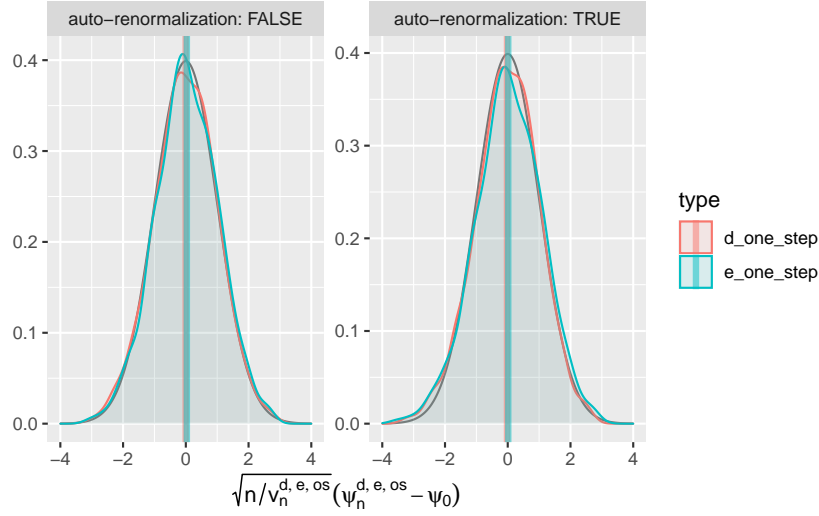


Figure 9.1: Kernel density estimators of the law of two one-step-G-computation estimators of ψ_0 (recentered with respect to ψ_0 , and renormalized). The estimators respectively hinge on algorithms $\widehat{\mathcal{A}}_{\bar{Q},1}$ (d) and $\widehat{\mathcal{A}}_{\bar{Q},\text{kNN}}$ (e) to estimate \bar{Q}_0 , and on one-step correction. Two renormalization schemes are considered, either based on an estimator of the asymptotic variance (left) or on the empirical variance computed across the `iter` independent replications of the estimators (right). We emphasize that the x -axis ranges differ between the left and right plots.

It seems that the one-step correction performs quite well (in particular, compare `bias_de` with `bias_de_one_step`):

```
bind_rows(bias_de, bias_de_one_step) %>%
  filter(!auto_renormalization) %>%
  arrange(type)
#> # A tibble: 4 x 3
#>   type      auto_renormalization      bias
#>   <chr>      <lgl>                <dbl>
#> 1 d          FALSE                0.240
#> 2 d_one_step FALSE            -0.00668
#> 3 e          FALSE                0.122
#> 4 e_one_step FALSE                0.0333
```

What about the estimation of the asymptotic variance, and of the mean-square errors of the estimators?

```
psi_hat_de %>%
  full_join(psi_hat_de_one_step) %>%
  filter(auto_renormalization) %>%
  group_by(type) %>%
  summarize(sd = mean(sig_n),
            se = sd(psi_n),
            mse = mean((psi_n - psi_zero)^2) * n()) %>%
  arrange(type)
#> # A tibble: 4 x 4
#>   type      sd      se      mse
#>   <chr>    <dbl> <dbl> <dbl>
#> 1 d          0.00208 0.0178 0.336
#> 2 d_one_step 0.0174 0.0174 0.302
#> 3 e          0.00289 0.0176 0.314
#> 4 e_one_step 0.0167 0.0176 0.309
```

The `sd` (*estimator* of the asymptotic standard deviation) and `se` (*empirical* standard deviation) entries are similar. This indicates that the inference of the asymptotic variance of the one-step estimators based on the influence curve is rather accurate for both the `d`- and `e`-variants that we implemented. As for the mean square error, it is diminished by the one-step update for both types `d` and `e`, the `e_one_step` estimator exhibiting the smallest mean square error.

9.4 Investigating further the one-step correction methodology

1. Use `estimate_Gbar` to create an oracle algorithm $\tilde{\mathcal{A}}_{\bar{G},s}$ for the estimation of \bar{G}_0 that, for any $s > 0$, estimates $\bar{G}_0(w)$ with

$$\bar{G}_n(w) \doteq \tilde{\mathcal{A}}_{\bar{G},s}(P_n)(w) \doteq \text{expit}(\text{logit}(\bar{G}_0(w)) + sZ)$$

where Z is a standard normal random variable.¹ What would happen if one chose $s = 0$ in the above definition? What happens when s converges to 0? Explain why the algorithm is said to be an *oracle algorithm*.

2. Use `estimate_Qbar` to create an oracle algorithm $\tilde{\mathcal{A}}_{\bar{Q},s}$ for the estimation of \bar{Q}_0 that, for any $s > 0$, estimates $\bar{Q}_0(a, w)$ with

$$\bar{Q}_n(a, w) \doteq \tilde{\mathcal{A}}_{\bar{Q},s}(P_n)(a, w) \doteq \text{expit}(\text{logit}(\bar{Q}_0(a, w)) + sZ)$$

where Z is a standard normal random variable. The comments made about $\tilde{\mathcal{A}}_{\bar{G},s}$ in the above problem also apply to $\tilde{\mathcal{A}}_{\bar{Q},s}$.

3. Reproduce the simulation study developed in Sections 8.4.3 and 9.3 with the oracle algorithms $\tilde{\mathcal{A}}_{\bar{G},s}$ and $\tilde{\mathcal{A}}_{\bar{Q},s'}$ substituted for used in these sections. Change the values of $s, s' > 0$ and compare how well the estimating procedure performs depending on the product ss' . What do you observe? We invite you to refer to Section C.2.1.

¹Note that the algorithm does not really to be trained.

Section 10

Targeted minimum loss-based estimation

10.1 Motivations

10.1.1 Falling outside the parameter space

Section 9 introduced the one-step corrected estimator ψ_n^{os} of ψ_0 . It is obtained by adding a correction term to an initial plug-in estimator $\Psi(P_n^\circ)$, resulting in an estimator that is asymptotically linear with influence curve $\text{IC} = D^*(P_0)$ under mild conditions (see Section 9.2 and the detailed proof there in Appendix C.2).

Unfortunately, the one-step estimator lacks a desirable feature of a plug-in estimator: plug-in estimators always lie in the parameter space whereas a one-step estimator does not necessarily do so. For example, it must also be true that $\psi_0 = \Psi(P_0) \in [-1, 1]$ yet it may be the case that $\psi_n^{\text{os}} \notin [-1, 1]$.

It is typically easy to shape an algorithm $\widehat{\mathcal{A}}_{\bar{Q}}$ for the estimation of \bar{Q}_0 to output estimators \bar{Q}_n that, like \bar{Q}_0 , take their values in $[0, 1]$. The plug-in estimator ψ_n (8.1) based on such a \bar{Q}_n necessarily satisfies $\psi_n \in [-1, 1]$. However, the one-step estimator derived from ψ_n may fall outside of the interval if the correction term $P_n D^*(P_n^\circ)$ is large.

10.1.2 The influence curve equation

Upon closer examination of the influence curve $D^*(P_n^\circ)$, we see that this may occur more frequently when $\ell \bar{G}_n(A_i, W_i)$ is close to zero for at least some $1 \leq i \leq n$. In words, this may happen if there are observations in our data set that we observed under actions A_i that were estimated to be unlikely given their respective contexts W_i . In such cases, $D^*(P_n^\circ)(O_i)$, and

consequently the one-step correction term, may be large and cause the one-step estimate to fall outside $[-1, 1]$.

Another way to understand this behavior is to recognize the one-step estimator as an initial plug-in estimator that is corrected *in the parameter space of ψ_0* . One of the pillars of targeted learning is to perform, instead, a correction *in the parameter space of \bar{Q}_0* .

In particular, consider a law P_n^* estimating P_0 that is compatible with the estimators \bar{Q}_n^* , \bar{G}_n , and $Q_{n,W}$, but moreover is such that

$$P_n D^*(P_n^*) = 0 \quad (10.1)$$

or, at the very least,

$$P_n D^*(P_n^*) = o_{P_0}(1/\sqrt{n}). \quad (10.2)$$

Achieving (10.1) is called *solving the efficient influence curve equation*. Likewise, achieving (10.2) is called *solving approximately the influence curve equation*.

If such estimators can be generated indeed, then the plug-in estimator

$$\psi_n^* \doteq \Psi(P_n^*) = \int (\bar{Q}_n^*(1, w) - \bar{Q}_n^*(0, w)) dQ_{n,W}(w)$$

is asymptotically linear with influence curve $IC = D^*(P_0)$, under mild conditions. Moreover, by virtue of its plug-in construction, it has the additional property that in finite-samples ψ_n^* will always obey bounds on the parameter space.

10.1.3 A basic fact on the influence curve equation

Our strategy for constructing such a plug-in estimate begins by generating an initial estimator \bar{Q}_n of \bar{Q}_0 based on an algorithm $\widehat{\mathcal{A}}_{\bar{Q}}$ and an estimator \bar{G}_n of \bar{G}_0 based on an algorithm $\widehat{\mathcal{A}}_{\bar{G}}$. These initial estimators should strive to be as close as possible to their respective targets. We use the empirical distribution $Q_{n,W}$ as an estimator of $Q_{0,W}$.

Now, recall the definition of D_1^* (3.4) and note that for *any* estimator \bar{Q}_n^* of \bar{Q}_0 and a law P_n^* that is compatible with \bar{Q}_n^* and $Q_{n,W}$,

$$P_n D_1^*(P_n^*) = 0.$$

The proof can be found there in Appendix C.4.1.

In words, this shows that so long as we use the empirical distribution $Q_{n,W}$ to estimate $Q_{0,W}$, by its very construction achieving (10.1) or (10.2) is equivalent to solving

$$P_n D_2^*(P_n^*) = 0 \quad (10.3)$$

or

$$P_n D_2^*(P_n^*) = o_{P_0}(1/\sqrt{n}). \quad (10.4)$$

It thus remains to devise a strategy for ensuring that $P_n D_2^*(P_n^*) = 0$ or $o_{P_0}(1/\sqrt{n})$.

10.2 Targeted fluctuation

Our approach to solving (10.3)¹ hinges on revising our initial estimator \bar{Q}_n of \bar{Q}_0 . We propose a method for building an estimator of \bar{Q}_0 that is “near to” \bar{Q}_n , but is such that for any law P_n^* that is compatible with this revised estimator, $P_n D^*(P_n^*) = 0$.² Because \bar{Q}_n is our best (initial) estimator of \bar{Q}_0 , the new estimator that we shall build should be *at least as good* an estimator of \bar{Q}_0 as \bar{Q}_n . So first, we must propose a way to move between regression functions, and then we must propose a way to move to a new regression function that fits the data at least as well as \bar{Q}_n .

Instead of writing “propos[ing] a way to move between regression functions” we may also have written “proposing a way to *fluctuate* a regression function”, thus suggesting very opportunely that the notion of fluctuation as discussed in Section 3.3 may prove instrumental to achieve the former objective.

10.2.1 2 Fluctuating indirectly

Let us resume the discussion where we left it at the end of Section 3.3.1. It is easy to show that the fluctuation $\{P_h : h \in H\}$ of P in direction of s in \mathcal{M} induces a fluctuation $\{\bar{Q}_h : h \in H\}$ of $\bar{Q} = Q_h|_{h=0}$ in the space $\mathcal{Q} \doteq \{\bar{Q} : P \in \mathcal{M}\}$ of regression functions induced by model \mathcal{M} . Specifically we show there in Appendix C.4.2 that, for every $h \in H$, the conditional mean $\bar{Q}_h(A, W)$ of Y given (A, W) under P_h is given by

$$\bar{Q}_h(A, W) \doteq \frac{\bar{Q}(A, W) + hE_P(Ys(O)|A, W)}{1 + hE_P(s(O)|A, W)}.$$

We note that if $s(O)$ depends on O only through (A, W) then, abusing notation and writing $s(A, W)$ for $s(O)$,

$$\begin{aligned} \bar{Q}_h(A, W) &= \frac{\bar{Q}(A, W) + hE_P(Ys(A, W)|A, W)}{1 + hE_P(s(A, W)|A, W)} \\ &= \frac{\bar{Q}(A, W) + hs(A, W)\bar{Q}(A, W)}{1 + hs(A, W)} \\ &= \bar{Q}(A, W). \end{aligned} \tag{10.5}$$

In words, \bar{Q} is not fluctuated at all, that is, the laws P_h that are elements of the fluctuation share the same conditional mean of Y given (A, W) .³

However we find it easier in the present context, notably from a computational perspective, to fluctuate \bar{Q}_n *directly* in \mathcal{Q} , as opposed to *indirectly* through a fluctuation defined in \mathcal{M} of a law compatible with \bar{Q}_n . The next section introduces such a direct fluctuation.

¹or (10.4).

²or $P_n D^*(P_n^*) = o_{P_0}(1/\sqrt{n})$.

³In fact, more generally, the conditional *law* of Y given (A, W) is not fluctuated. See the corresponding problem in Section 10.2.3.

10.2.2 Fluctuating directly

Set arbitrarily $\bar{Q} \in \mathcal{Q}$. The (direct) fluctuation of \bar{Q} that we propose to consider depends on a user-supplied \bar{G} . For any \bar{G} such that $0 < \ell \bar{G}(A, W) < 1$, P_0 -almost surely, the \bar{G} -specific fluctuation model for \bar{Q} is

$$\mathcal{Q}(\bar{Q}, \bar{G}) \doteq \left\{ (w, a) \mapsto \bar{Q}_h(a, w) \doteq \text{expit} \left(\text{logit}(\bar{Q}(a, w)) + h \frac{2a - 1}{\ell \bar{G}(a, w)} \right) : t \in \mathbb{R} \right\} \subset \mathcal{Q}. \quad (10.6)$$

Fluctuation $\mathcal{Q}(\bar{Q}, \bar{G})$ is a one-dimensional parametric model (indexed by the real-valued parameter h) that goes through \bar{Q} (at $h = 0$). For each $h \in \mathbb{R}$, $\bar{Q}_h \in \mathcal{Q}$ is the conditional mean of Y given (A, W) under infinitely many laws $P \in \mathcal{M}$.

The following chunk of code represents three elements of the fluctuations $\mathcal{Q}(\bar{Q}_0, \bar{G}_0)$ and $\mathcal{Q}(\bar{Q}_{n, \text{trees}}, \bar{G}_0)$, where $\bar{Q}_{n, \text{trees}}$ is an estimator of \bar{Q}_0 derived by the boosted trees algorithm (see Section 7.6.3).

```
Qbar_hminus <- fluctuate(Qbar, Gbar, h = -1)
Qbar_hplus <- fluctuate(Qbar, Gbar, h = +1)

Qbar_trees <- wrapper(Qbar_hat_trees, FALSE)
Qbar_trees_hminus <- fluctuate(Qbar_trees, Gbar, h = -1)
Qbar_trees_hplus <- fluctuate(Qbar_trees, Gbar, h = +1)

tibble(w = seq(0, 1, length.out = 1e3)) %>%
  mutate(truth_0_1 = Qbar(cbind(A = 1, W = w)),
         truth_0_0 = Qbar(cbind(A = 0, W = w)),
         trees_0_1 = Qbar_trees(cbind(A = 1, W = w)),
         trees_0_0 = Qbar_trees(cbind(A = 0, W = w)),
         truth_hminus_1 = Qbar_hminus(cbind(A = 1, W = w)),
         truth_hminus_0 = Qbar_hminus(cbind(A = 0, W = w)),
         trees_hminus_1 = Qbar_trees_hminus(cbind(A = 1, W = w)),
         trees_hminus_0 = Qbar_trees_hminus(cbind(A = 0, W = w)),
         truth_hplus_1 = Qbar_hplus(cbind(A = 1, W = w)),
         truth_hplus_0 = Qbar_hplus(cbind(A = 0, W = w)),
         trees_hplus_1 = Qbar_trees_hplus(cbind(A = 1, W = w)),
         trees_hplus_0 = Qbar_trees_hplus(cbind(A = 0, W = w))) %>%
  pivot_longer(-w, names_to = "f", values_to = "value") %>%
  extract(f, c("f", "h", "a"), "([^\_]+)_([^\_]+)_([01]+)") %>%
  mutate(f = ifelse(f == "truth", "Q_0", "Q_n"),
         h = factor(ifelse(h == "0", 0, ifelse(h == "hplus", 1, -1)))) %>%
  mutate(a = paste0("a=", a),
         fh = paste0("(", f, ", ", h, ")")) %>%
  ggplot +
```

```
geom_line(aes(x = w, y = value, color = h, linetype = f, group = fh),
          size = 1) +
labs(y = bquote(paste(f[h] (a,w))),
     title = bquote("Visualizing three elements of two fluctuations of"
                     ~ bar(Q)[0] ~ "and" ~ bar(Q)[n])) +
ylim(NA, 1) +
facet_wrap(~ a)
```

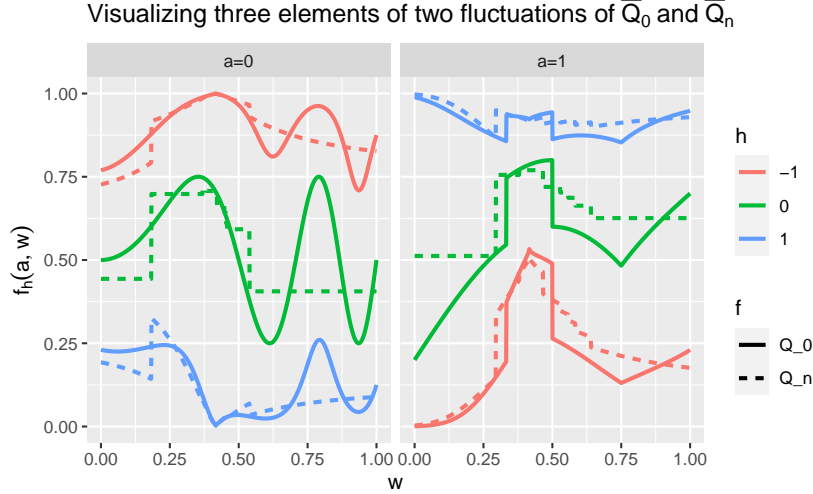


Figure 10.1: Representing three elements \bar{Q}_h of the fluctuations $\mathcal{Q}(\bar{Q}_0, \bar{G}_0)$ and $\mathcal{Q}(\bar{Q}_{n, \text{trees}}, \bar{G}_0)$, respectively, where $\bar{Q}_{n, \text{trees}}$ is an estimator of \bar{Q}_0 derived by the boosted trees algorithm (see Section 7.6.3). The three elements correspond to $h = -1, 0, 1$. When $h = 0$, \bar{Q}_h equals either \bar{Q}_0 or $\bar{Q}_{n, \text{trees}}$, depending on which fluctuation is roamed.

10.2.3 More on fluctuations

1. Justify the series of equalities in (10.5).
2. Justify that, in fact, if $s(O)$ depends on O only through (A, W) then the conditional law of Y given (A, W) under P_h equals that under P .

10.2.4 Targeted roaming of a fluctuation

Recall that our goal is to build an estimator of \bar{Q}_0 that is *at least as good* as \bar{Q}_n . We will look for this enhanced estimator in the fluctuation $\mathcal{Q}(\bar{Q}_n, \bar{G}_n)$ where \bar{G}_n is an estimator of \bar{G}_0 that is bounded away from 0 and 1. Thus, the estimator writes as \bar{Q}_{n, h_n} for some data-driven $h_n \in \mathbb{R}$. We will clarify why we do so at a later time

To assess the performance of all the candidates included in the fluctuation, we formally rely on the empirical risk function $h \mapsto E_{P_n} (L_y(\bar{Q}_{n,h})(O))$ where

$$E_{P_n} (L_y(\bar{Q}_{n,h})(O)) = \frac{1}{n} \sum_{i=1}^n L_y(\bar{Q}_{n,h})(O_i)$$

and the logistic (or negative binomial) loss function L_y is given by

$$-L_y(f)(O) \doteq Y \log f(A, W) + (1 - Y) \log (1 - f(A, W))$$

for any function $f : \{0, 1\} \times [0, 1] \rightarrow [0, 1]$. This loss function is the counterpart of the loss function L_a defined in (7.1). The justification that we gave in Section 7.4.1 of the relevance of L_a also applies here, *mutatis mutandis*. In summary, the oracle risk $E_{P_0} (L_y(f)(O))$ of f is a real-valued measure of discrepancy between \bar{Q}_0 and f ; \bar{Q}_0 minimizes $f \mapsto E_{P_0} (L_y(f)(O))$ over the set of all (measurable) functions $f : [0, 1] \times \{0, 1\} \times [0, 1] \rightarrow [0, 1]$; and a minimizer $h_0 \in \mathbb{R}$ of $h \mapsto E_{P_0} (L_y(\bar{Q}_{n,h})(O))$ identifies the element of fluctuation $\mathcal{Q}(\bar{Q}_n, \bar{G}_n)$ that is closest to \bar{Q}_0 (some details are given there in Appendix B.6).

It should not come as a surprise after this discussion that the aforementioned data-driven h_n is chosen to be the minimizer of the empirical risk function, *i.e.*,

$$h_n \doteq \arg \min_{h \in \mathbb{R}} E_{P_n} (L_y(\bar{Q}_{n,h})(O)).$$

The criterion is convex so the optimization program is well-posed.

The next chunk of code illustrates the search of an approximation of h_n over a grid of candidate values.

```

candidates <- seq(-0.01, 0.01, length.out = 1e4)
W <- obs[1:1e3, "W"]
A <- obs[1:1e3, "A"]
Y <- obs[1:1e3, "Y"]
lGAW <- compute_lGbar_hatAW(A, W, Gbar_hat)
QAW <- compute_Qbar_hatAW(A, W, Qbar_hat_trees)
risk <- sapply(candidates,
  function(h) {
    QAW_h <- expit(logit(QAW) + h * (2 * A - 1) / lGAW)
    -mean(Y * log(QAW_h) + (1 - Y) * log(1 - QAW_h))
  })
idx_min <- which.min(risk)
idx_zero <- which.min(abs(candidates))[1]
labels <- c(expression(R[n] (bar(Q) [list(n,hn)] ^list(o))),
  expression(R[n] (bar(Q) [list(n,0)] ^list(o))))
risk %>% enframe %>%

```

```

mutate(h = candidates) %>%
filter(abs(h - h[idx_min]) <= abs(h[idx_min])) %>%
ggplot() +
geom_point(aes(x = h, y = value), color = "#CC6666") +
geom_vline(xintercept = c(0, candidates[idx_min])) +
geom_hline(yintercept = c(risk[idx_min], risk[idx_zero])) +
scale_y_continuous(
  bquote("empirical logistic risk, " ~ R[n](bar(Q)[list(n,h)]^list(o))),
  trans = "exp", labels = NULL,
  sec.axis = sec_axis(~ .,
    breaks = c(risk[idx_min], risk[idx_zero]),
    labels = labels))

```

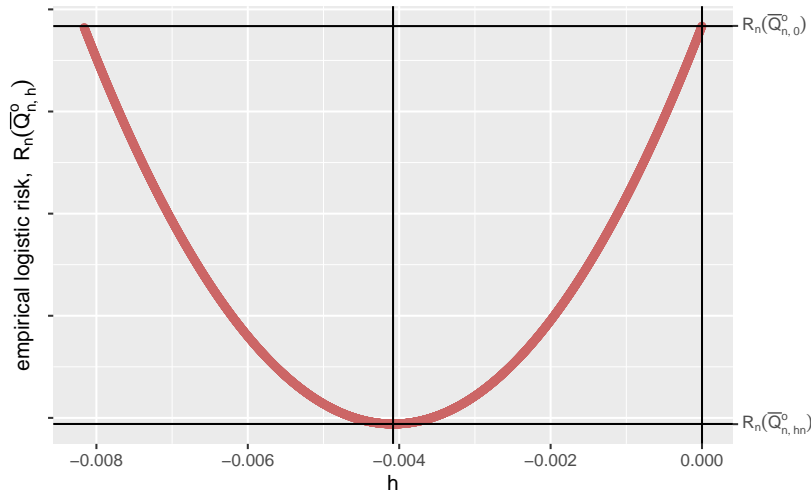


Figure 10.2: Representing the evolution of the empirical risk function as h ranges over a grid of values. One sees that the risk at $h = 0$ (*i.e.*, the risk of \bar{Q}_n) is larger than the minimal risk, achieved at $h \approx -0.004$ (which must be close to that of the optimal \bar{Q}_{n,h_n}).

Figure 10.2 reveals how moving away slightly from $h = 0$ to the left (*i.e.*, to h_n equal to -0.004 , rounded to three decimal places) entails a decrease of the empirical risk. The gain is modest at the scale of the empirical risk, but considerable in terms of inference, as we explain below.

10.2.5 Justifying the form of the fluctuation

Let us define $\bar{Q}_n^* \doteq \bar{Q}_{n,h_n}$. We justify in two steps our assertion that moving from $\bar{Q}_n|_{h=0} = \bar{Q}_n$ to \bar{Q}_n^* along fluctuation $\mathcal{Q}(\bar{Q}_n, \bar{G}_n)$ has a considerable impact for the inference of ψ_0 .

First, we note that there is no need to iterate the updating procedure. Specifically, even if we tried to fluctuate \bar{Q}_n^* along the fluctuation $\mathcal{Q}(\bar{Q}_n^*, \bar{G}_n) = \{\bar{Q}_{n,h'}^* : h' \in \mathbb{R}\}$ defined like $\mathcal{Q}(\bar{Q}_n, \bar{G}_n)$ (10.6) with \bar{Q}_{n,h_n} substituted for \bar{Q}_n , then we would not move at all. This is obvious because there is a one-to-one smooth correspondence between the parameter h' indexing $\mathcal{Q}(\bar{Q}_n^*, \bar{G}_n)$ and the parameter h indexing $\mathcal{Q}(\bar{Q}_n, \bar{G}_n)$ (namely, $h' = h + h_n$). Therefore, the derivative of (the real-valued function over \mathbb{R}) $h \mapsto \mathbb{E}_{P_n}(L_y(\bar{Q}_{n,h})(O))$ evaluated at its minimizer h_n equals 0. Equivalently (see there in Appendix C.4.3 for a justification of the last but one equality below),

$$\begin{aligned}
& \frac{d}{dh} \mathbb{E}_{P_n} (L_y(\bar{Q}_{n,h}^*)(O)) \Big|_{h=0} \\
&= -\frac{1}{n} \frac{d}{dh} \sum_{i=1}^n \left(Y_i \log \bar{Q}_{n,h}^*(A_i, W_i) + (1 - Y_i) \log (1 - \bar{Q}_{n,h}^*(A_i, W_i)) \right) \Big|_{h=0} \\
&= -\frac{1}{n} \sum_{i=1}^n \left(\frac{Y_i}{\bar{Q}_n^*(A_i, W_i)} - \frac{1 - Y_i}{1 - \bar{Q}_n^*(A_i, W_i)} \right) \times \frac{d}{dh} \bar{Q}_{n,h}^*(A_i, W_i) \Big|_{h=0} \\
&= -\frac{1}{n} \sum_{i=1}^n \frac{Y_i - \bar{Q}_n^*(A_i, W_i)}{\bar{Q}_n^*(A_i, W_i) \times (1 - \bar{Q}_n^*(A_i, W_i))} \frac{d}{dh} \bar{Q}_{n,h}^*(A_i, W_i) \Big|_{h=0} \\
&= -\frac{1}{n} \sum_{i=1}^n \frac{2A_i - 1}{\ell \bar{G}_n(A_i, W_i)} (Y_i - \bar{Q}_n^*(A_i, W_i)) = 0.
\end{aligned} \tag{10.7}$$

Second, let P_n^* be a law in \mathcal{M} such that the Q_W , \bar{G} and \bar{Q} features of P_n^* equal $Q_{n,W}$, \bar{G}_n and Q_n^* , respectively. In other words, P_n^* is compatible with $Q_{n,W}$, \bar{G}_n and \bar{Q}_n^* .⁴ Note that the last equality in (10.7) equivalently writes as

$$P_n D_2^*(P_n^*) = 0.$$

Thus the (direct) fluctuation solves (10.3). Now, we have already argued in Section 10.1.3 that it also holds that

$$P_n D_1^*(P_n^*) = 0.$$

Consequently, P_n^* solves the efficient influence curve equation, that is, satisfies (10.1). As argued in Section 10.1.2, it thus follows that the plug-in estimator

$$\psi_n^* \doteq \Psi(P_n^*) = \int (\bar{Q}_n^*(1, w) - \bar{Q}_n^*(0, w)) dQ_{n,W}(w)$$

is asymptotically linear with influence curve $\text{IC} = D^*(P_0)$, under mild conditions. Moreover, by virtue of its plug-in construction, it has the additional property that in finite-samples ψ_n^* will always obey bounds on the parameter space.

⁴In Section 9.1, we defined P_n^* similarly with \bar{Q}_n substituted for \bar{Q}_n^* .

10.2.6 Alternative fluctuation

The following exercises will have you consider an alternative means of performing a fluctuation. For $a = 0, 1$, consider the following fluctuation model for $\bar{Q}^a \doteq \bar{Q}(a, \cdot)$:

$$\mathcal{Q}^a(\bar{Q}^a) \doteq \{w \mapsto \bar{Q}_h^a(w) \doteq \text{expit}(\text{logit}(\bar{Q}(a, w)) + h) : h \in \mathbb{R}\} \subset \mathcal{Q}. \quad (10.8)$$

Let

$$\mathcal{Q}^{\text{alt}}(\bar{Q}) \doteq \{(a, w) \mapsto \bar{Q}_{h_0, h_1}^a(a, w) \doteq a \times \bar{Q}_{h_1}^1(w) + (1 - a) \bar{Q}_{h_0}^0(w) : h_0, h_1 \in \mathbb{R}\}$$

be the fluctuation model for \bar{Q} that is implied by the two submodels for \bar{Q}^1 and \bar{Q}^0 .

Also for a given \bar{G} satisfying that $0 < \ell \bar{G}(A, W) < 1$, P_0 -almost surely, and both $a = 0, 1$, consider the loss function $L_{y, \bar{G}}^a$ given by

$$L_{y, \bar{G}}^a(f)(A, W) \doteq \frac{\mathbf{1}\{A = a\}}{\ell \bar{G}(A, W)} L_y(f)(O)$$

for any function $f : \{0, 1\} \times [0, 1] \rightarrow [0, 1]$, where L_y is defined in (10.2.4) above. It yields the empirical risk function

$$(h_0, h_1) \mapsto \sum_{a=0,1} \mathbb{E}_{P_n} \left(L_{y, \bar{G}}^a(\bar{Q}_{n, h_a}^a)(O) \right).$$

1. Comment on the differences between these fluctuation model and loss function compared to those discussed above.
2. Visualize three elements of $\mathcal{Q}^{\text{alt}}(\bar{Q}_0)$ and $\mathcal{Q}^{\text{alt}}(\bar{Q}_n)$: choose three values for (h_0, h_1) and reproduce Figure 10.1.
3. Argue that in order to minimize the empirical risk over all $(h_0, h_1) \in \mathbb{R}^2$, we may minimize over $h_0 \in \mathbb{R}$ and $h_1 \in \mathbb{R}$ separately.
4. Visualize how the empirical risk with $\bar{G} = \bar{G}_n$ varies for different elements \bar{Q}_{n, h_0, h_1} of $\mathcal{Q}(\bar{Q}_n)$. For simplicity (and with the justification of problem 3), you may wish to make a separate figure (like Figure 10.2) for $a = 0, 1$ that illustrates how the empirical risk varies as a function of h_a while setting $h_{1-a} = 0$.
5. \geq Justify the validity of $L_{y, \bar{G}}^a$ as a loss function for \bar{Q}_0^a : show that amongst all functions that map w to $(0, 1)$, the true risk $\mathbb{E}_{P_0} \left(L_{y, \bar{G}}^a(f)(O) \right)$ is minimized when $f = \bar{Q}_0^a$.
6. \geq Argue that your answer to problem 2 also implies that the summed loss function $\sum_{a=0,1} L_{y, \bar{G}}^a$ is valid for \bar{Q} .
7. \geq Justify the combination of these loss function and fluctuation by repeating the calculation in equation (10.7) above, *mutatis mutandis*.

10.3 Summary and perspectives

The procedure laid out in Section 10 is called *targeted minimum loss-based estimation* (TMLE). The nomenclature derives from its logistics. We first generated an (un-targeted) initial estimator of $\Psi(P_0)$ by substituting for P_0 a law P_n° compatible with initial estimators of some Ψ -specific relevant nuisance parameters. Then through loss-minimization, we built a *targeted* estimator by substituting for P_n° a law P_n^* compatible with the nuisance parameters that we updated in a targeted fashion.

The TMLE procedure was coined in 2006 by Mark van der Laan and Dan Rubin [van der Laan and Rubin, 2006]. It has since then been developed and applied in a great variety of contexts. We refer to the monographies [van der Laan and Rose, 2011] and [van der Laan and Rose, 2018] for a rich overview.

In summary, targeted learning bridges the gap between formal inference of finite-dimensional parameters $\Psi(P_0)$ of the law P_0 of the data, via bootstrapping or influence curves, and data-adaptive, loss-based, machine learning estimation of Ψ -specific infinite-dimensional features thereof (the so-called nuisance parameters). A typical example concerns the super learning-based, targeted estimation of effect parameters defined as identifiable versions of causal quantities. The TMLE algorithm integrates completely the estimation of the relevant nuisance parameters by super learning [van der Laan et al., 2007]. Under mild assumptions, the targeting step removes the bias of the initial estimators of the targeted effects. The resulting TMLEs enjoy many desirable statistical properties: among others, by being substitution estimators, they lie in the parameter space; they are often double-robust; they lend themselves to the construction of confidence regions.

The scientific community is always engaged in devising and promoting enhanced principles for sounder research through the better design of experimental and nonexperimental studies and the development of more reliable and honest statistical analyses. By focusing on prespecified analytic plans and algorithms that make realistic assumptions in more flexible nonparametric or semiparametric statistical models, targeted learning has been at the fore of this concerted effort. Under this light, targeted learning notably consists in translating knowledge about the data and underlying data-generating mechanism into a realistic model; in expressing the research question under the form of a statistical estimation problem; in analyzing the statistical estimation problem within the frame of the model; in developing *ad hoc* algorithms grounded in theory and tailored to the question at stake to map knowledge and data into an answer coupled to an assessment of its trustworthiness.

Quoting [van der Laan and Rose, 2018]:

Over the last decade, targeted learning has been established as a reliable framework for constructing effect estimators and prediction functions. The continued development of targeted learning has led to new solutions for existing problems in many data structures in addition to discoveries in varied applied areas. This has included work in randomized controlled trials, parameters defined by

a marginal structural model, case-control studies, collaborative TMLE, missing and censored data, longitudinal data, effect modification, comparative effectiveness research, aging, cancer, occupational exposures, plan payment risk adjustment, and HIV, as well as others. In many cases, these studies compared targeted learning techniques to standard approaches, demonstrating improved performance in simulations and realworld applications.

It is now time to resume our introduction to TMLE and to carry out an empirical investigation of its statistical properties in the context of the estimation of ψ_0 .

10.4 Empirical investigation

10.4.1 A first numerical application

Let us illustrate the principle of targeted minimum loss estimation by updating the G-computation estimator built on the $n = 1000$ first observations in `obs` by relying on $\widehat{\mathcal{A}}_{\bar{Q}, \text{knn}}$, that is, on the algorithm for the estimation of \bar{Q}_0 as it is implemented in `estimate_Qbar` with its argument `algorithm` set to the built-in `kknn_algo` (see Section 7.6.2). In Section 9.3, we performed a one-step correction of the same initial estimator.

The algorithm has been trained earlier on this data set and produced the object `Qbar_hat_kknn`. The following chunk of code prints the initial estimator `psin_kknn`, its one-step update `psin_kknn_os`, then applies the targeting step and presents the resulting estimator:

```
(psin_kknn)
#> # A tibble: 1 x 2
#>   psi_n sig_n
#>   <dbl> <dbl>
#> 1 0.0887 0.00245
(psin_kknn_os)
#> # A tibble: 1 x 3
#>   psi_n sig_n crit_n
#>   <dbl> <dbl> <dbl>
#> 1 0.0888 0.0162 0.000124
(psin_kknn_tmle <- apply_targeting_step(head(obs, 1e3),
                                         wrapper(Gbar_hat, FALSE),
                                         wrapper(Qbar_hat_kknn, FALSE)))

#> # A tibble: 1 x 3
#>   psi_n sig_n crit_n
#>   <dbl> <dbl> <dbl>
#> 1 0.0888 0.0162 -1.01e-9
```

In the call to `apply_targeting_step` we provide (i) the data set at hand (first line), (ii) the estimator `Gbar_hat` of \bar{G}_0 that we built earlier by using algorithm $\hat{\mathcal{A}}_{\bar{G},1}$ (second line; see Section 7.4.2), (iii) the estimator `Qbar_hat_kknn` of \bar{Q}_0 (third line). Apparently, in this particular example, the one-step correction and targeted correction updater similarly the initial estimator.

10.4.2 A computational exploration

1. Consult the man page of function `apply_targeting_step` (run `?apply_targeting_step`) and explain what is the role of its input `epsilon`.
2. Run the chunk of code below. What does it do? Hint: check out the chunks of code of Sections 7.6.2, 8.2.1 and 10.4.1.

```
epsilon <- seq(-1e-2, 1e-2, length.out = 1e2)
Gbar_hat_w <- wrapper(Gbar_hat, FALSE)
Qbar_kknn <- wrapper(Qbar_hat_kknn, FALSE)

psi_trees_epsilon <- sapply(epsilon, function(h) {
  apply_targeting_step(head(obs, 1e3), Gbar_hat_w,
                        Qbar_trees, epsilon = h) %>%
    select(psi_n, crit_n) %>% as.matrix
})
idx_trees <- which.min(abs(psi_trees_epsilon[2, ]))

psi_kknn_epsilon <- sapply(epsilon, function(h) {
  apply_targeting_step(head(obs, 1e3), Gbar_hat_w,
                        Qbar_kknn, epsilon = h) %>%
    select(psi_n, crit_n) %>% as.matrix
})
idx_kknn <- which.min(abs(psi_kknn_epsilon[2, ]))

rbind(t(psi_trees_epsilon), t(psi_kknn_epsilon)) %>% as_tibble %>%
  rename("psi_n" = V1, "crit_n" = V2) %>%
  mutate(type = rep(c("trees", "kknn"), each = length(epsilon))) %>%
  ggplot() +
  geom_point(aes(x = crit_n, y = psi_n, color = type)) +
  geom_vline(xintercept = 0) +
  geom_hline(yintercept = c(psi_trees_epsilon[1,idx_trees],
                           psi_kknn_epsilon[1,idx_kknn])) +
  labs(x = bquote(paste(P[n]~D~"*", (P[list(n,h)]^o))),
       y = bquote(Psi(P[list(n,h)]^o)))
```

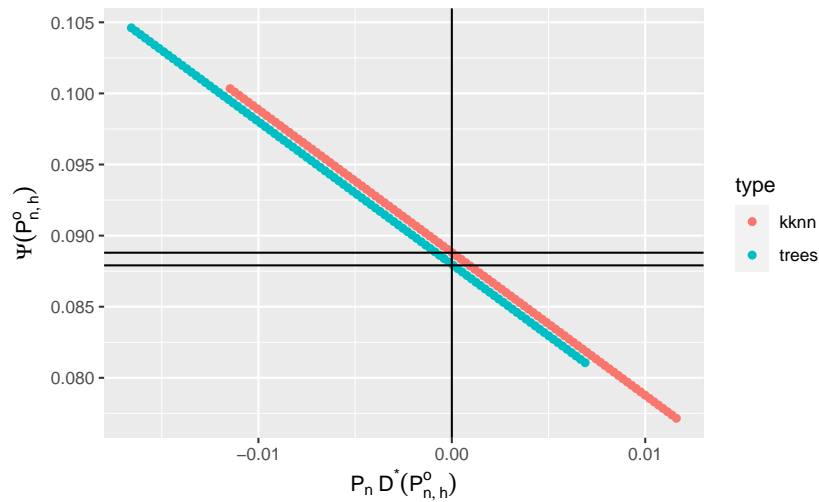


Figure 10.3: Figure produced when running the chunk of code from problem 2 in Section 10.4.2.

3. Discuss the fact that the colored curves in Figure 10.3 look like segments.

10.4.3 Empirical investigation

To assess more broadly what is the impact of the targeting step, let us apply it to the estimators that we built in Section 8.4.3. In Section 9.3, we applied the one-step correction to the same estimators.

The object `learned_features_fixed_sample_size` already contains the estimated features of P_0 that are needed to perform the targeting step on the estimators ψ_n^d and ψ_n^e , thus we merely have to call the function `apply_targeting_step`.

```
psi_tmle <- learned_features_fixed_sample_size %>%
  mutate(tmle_d =
    pmap(list(obs, Gbar_hat, Qbar_hat_d),
      ~ apply_targeting_step(as.matrix(..1),
        wrapper(..2, FALSE),
        wrapper(..3, FALSE))),
    tmle_e =
    pmap(list(obs, Gbar_hat, Qbar_hat_e),
      ~ apply_targeting_step(as.matrix(..1),
        wrapper(..2, FALSE),
        wrapper(..3, FALSE)))) %>%
  select(tmle_d, tmle_e) %>%
  pivot_longer(c(`tmle_d`, `tmle_e`),
```

```

      names_to = "type", values_to = "estimates") %>%
extract(type, "type", "_(de)$") %>%
mutate(type = paste0(type, "_targeted")) %>%
unnest(estimates) %>%
group_by(type) %>%
mutate(sig_alt = sd(psi_n)) %>%
mutate(clt_ = (psi_n - psi_zero) / sig_n,
      clt_alt = (psi_n - psi_zero) / sig_alt) %>%
pivot_longer(c(`clt_`, `clt_alt`),
      names_to = "key", values_to = "clt") %>%
extract(key, "key", "_(.*)$") %>%
mutate(key = ifelse(key == "", TRUE, FALSE)) %>%
rename("auto_renormalization" = key)

(bias_tmle <- psi_tmle %>%
  group_by(type, auto_renormalization) %>%
  summarize(bias = mean(clt)) %>% ungroup)
#> # A tibble: 4 x 3
#>   type      auto_renormalization      bias
#>   <chr>      <lgl>                  <dbl>
#> 1 d_targeted FALSE                -0.00706
#> 2 d_targeted TRUE                 -0.0246
#> 3 e_targeted FALSE                 0.0353
#> 4 e_targeted TRUE                 0.0182

fig <- ggplot() +
  geom_line(aes(x = x, y = y),
    data = tibble(x = seq(-4, 4, length.out = 1e3),
      y = dnorm(x)),
    linetype = 1, alpha = 0.5) +
  geom_density(aes(clt, fill = type, colour = type),
    psi_tmle, alpha = 0.1) +
  geom_vline(aes(xintercept = bias, colour = type),
    bias_tmle, size = 1.5, alpha = 0.5) +
  facet_wrap(~ auto_renormalization,
    labeller =
      as_labeller(c(`TRUE` = "auto-renormalization: TRUE",
        `FALSE` = "auto-renormalization: FALSE")),
    scales = "free")

fig +
  labs(y = "",

```

```
x = bquote(paste(sqrt(n/v[n]~{"*"})*
                (psi[n]~{"*"} - psi[0])))
```

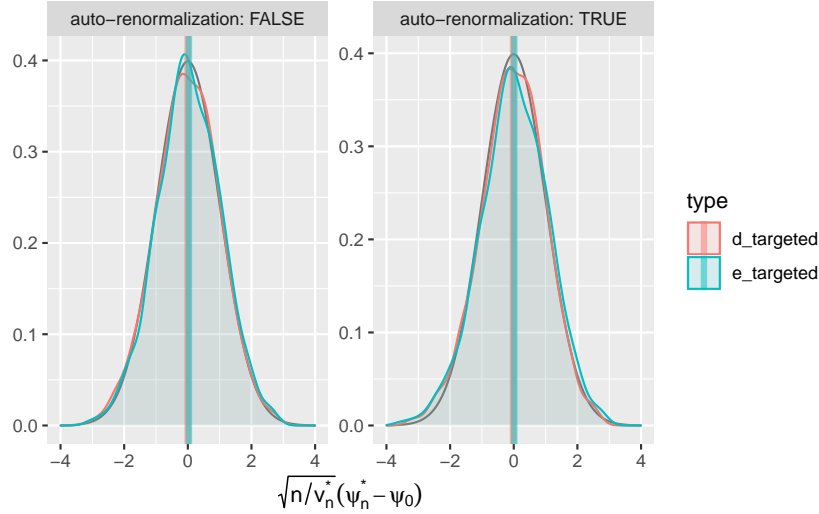


Figure 10.4: Kernel density estimators of the law of two targeted estimators of ψ_0 (re-centered with respect to ψ_0 , and renormalized). The estimators respectively hinge on algorithms $\widehat{\mathcal{A}}_{\bar{Q},1}$ (d) and $\widehat{\mathcal{A}}_{\bar{Q},\text{kNN}}$ (e) to estimate \bar{Q}_0 , and on a targeting step. Two renormalization schemes are considered, either based on an estimator of the asymptotic variance (left) or on the empirical variance computed across the `iter` independent replications of the estimators (right). We emphasize that the x -axis ranges differ between the left and right plots.

We see that the step of targeting is as promised: the bias of the resulting estimators is minimized relative to the naive estimators. Comparing these results to those obtain using one-step estimators (Section 9.3), we find quite similar performance between one-step and TMLE estimators.

Section 11

Closing words

The velocity of advances in machine learning make it an exciting time to work as a statistician. Clearly, statistical inference is more challenging when one considers the sort of infinite-dimensional statistical models that underlie these developments. Even defining some fundamental statistical notions, like efficiency, in these settings is a challenge. Constructing estimators that obtain these properties is more challenging still. We hope that this short guide has provided an approachable introduction to this exciting area of research.

Targeted learning is a vibrant and active field of research, with new developments happening along theoretical, applied, and computational axes. The **tlverse** software environment is actively being developed to provide researchers with new tools for utilizing these methods.

““

Appendix A

Notation

- \doteq , equal by definition to
- $\mathbf{1}\{S\}$, the indicator of statement S , which equals 1 if S is true and 0 otherwise.
- $O \doteq (W, A, Y)$, the generic summary of how one realization of the experiments of interest unfold, our generic observation; $W \in [0, 1]$ is the context of action, $A \in \{0, 1\}$ is the action undertaken, and $Y \in [0, 1]$ is the reward of action A in context W . We denote by $\mathcal{O} \doteq [0, 1] \times \{0, 1\} \times [0, 1]$ the set where a generic O takes its values.
- $P, P_0, \Pi_0, \Pi_h, \Pi'_0, \Pi'_h$, laws (on \mathcal{O}) for O .
- $Pf \doteq \mathbb{E}_P(f(O))$ for any law P for O and function f from \mathcal{O} to \mathbb{R}^p .
- $\|f\|_P^2 \doteq Pf^2 = \mathbb{E}_P(f(O)^2) = \int f(o)^2 dP(o)$, the square of the $L^2(P)$ -norm of f , a function from \mathcal{O} to \mathbb{R} .
- $\|f\|_\infty \doteq \sup_{o \in \mathcal{O}} |f(o)|$, the essential supremum of f , a function from \mathcal{O} to \mathbb{R} .
- P_n , the empirical measure. If the observations are O_1, \dots, O_n , then P_n is a law such that the generic random variable O drawn from P_n takes its values in $\{O_1, \dots, O_n\}$ in such a way that $O = O_i$ with probability n^{-1} for each $1 \leq i \leq n$.
- $\sqrt{n}(P_n - P)$, where P_n is the empirical measure associated to O_1, \dots, O_n drawn independently from P , the empirical process.
- $X_n = o_{P_0}(1)$ if X_n , a random variable built from O_1, \dots, O_n independently drawn from P_0 , converges in probability to zero, that is, if $P_0(|X_n| > t)$ converges to zero for all $t > 0$ as n goes to infinity. If $n^c X_n = o_{P_0}(1)$, then one also writes $X_n = o_{P_0}(n^{-c})$.
- $X_n = O_{P_0}(1)$ if X_n , a random variable built from O_1, \dots, O_n independently drawn from P_0 , is bounded in probability, that is if, for all $t > 0$ there exists $M > 0$ such that $\sup_{n \geq 1} P_0(|X_n| \geq M) \leq t$. If $n^c X_n = O_{P_0}(1)$, then one also writes $X_n = O_{P_0}(n^{-c})$.
- \mathcal{M} , the model, that is, the collection of *all* laws from which O can be drawn and that meet some constraints.

- $\mathcal{M}^{\text{empirical}}$, the collection of all discrete laws on $[0, 1] \times \{0, 1\} \times [0, 1]$, of which P_n is a distinguished element.
- $Q_W, Q_{0,W}$, marginal laws for W (under P and P_0 , respectively).
- $\bar{G}(W) \doteq \Pr_P(A = 1|W)$, $\bar{G}_0(W) \doteq \Pr_{P_0}(A = 1|W)$, conditional probabilities of action $A = 1$ given W (under P and P_0 , respectively). For each $a \in \{0, 1\}$, $\ell\bar{G}(a, W) \doteq \Pr_P(A = a|W)$ and $\ell\bar{G}_0(a, W) \doteq \Pr_{P_0}(A = a|W)$.
- $\bar{Q}(A, W) = \mathbb{E}_P(Y|A, W)$, $\bar{Q}_0(A, W) = \mathbb{E}_{P_0}(Y|A, W)$, the conditional means of Y given A and W (under P and P_0 , respectively).
- $\mathcal{Q} \doteq \{\bar{Q} : P \in \mathcal{M}\}$, the space of regression functions induced by model \mathcal{M} .
- $\mathcal{Q}(\bar{Q}, \bar{G}) \subset \mathcal{Q}$, \bar{G} -specific fluctuation model of \bar{Q} , see (10.6).
- $q_Y, q_{0,Y}$, conditional densities of Y given A and W (under P and P_0 , respectively).
- $\Psi : \mathcal{M} \rightarrow [0, 1]$, given by $\Psi(P) \doteq \int (\bar{Q}(1, w) - \bar{Q}(0, w)) dQ_W(w)$, the statistical mapping of interest.
- $\psi \doteq \Psi(P)$, $\psi_0 \doteq \Psi(P_0)$.
- $\widehat{\mathcal{A}}, \widehat{\mathcal{A}}_{\bar{G},1}, \widehat{\mathcal{A}}_{\bar{Q},1}$, algorithms to be trained on P_n , *i.e.*, mappings from $\mathcal{M}^{\text{empirical}}$ to the set where lives the feature targeted by the algorithm.
- $\widetilde{\mathcal{A}}_{\bar{G},s}, \widetilde{\mathcal{A}}_{\bar{Q},s}$, s -specific oracle algorithms ($s > 0$) that can use the true targeted features \bar{G}_0 and \bar{Q}_0 to produce predictions that are almost exact, up to a $N(0, s^2)$ random error term.
- L_a , the contex-specific logistic (or negative binomial) loss function, given by $-L_a(f)(A, W) \doteq A \log f(W) + (1 - A) \log(1 - f(W))$ for any function $f : [0, 1] \rightarrow [0, 1]$.
- L_y , the reward-specific logistic (or negative binomial) loss function, given by $-L_y(f)(O) \doteq Y \log f(A, W) + (1 - Y) \log(1 - f(A, W))$ for any function $f : \{0, 1\} \times [0, 1] \rightarrow [0, 1]$.

Appendix B

Basic results and their proofs

B.1 NPSEM

The experiment can also be summarized by a *nonparametric system of structural equations*: for some deterministic functions f_w , f_a , f_y and independent sources of randomness U_w , U_a , U_y ,

1. sample the context where the counterfactual rewards will be generated, the action will be undertaken and the actual reward will be obtained, $W = f_w(U_w)$;
2. sample the two counterfactual rewards of the two actions that can be undertaken, $Y_0 = f_y(0, W, U_y)$ and $Y_1 = f_y(1, W, U_y)$;
3. sample which action is carried out in the given context, $A = f_a(W, U_a)$;
4. define the corresponding reward, $Y = AY_1 + (1 - A)Y_0$;
5. summarize the course of the experiment with the observation $O = (W, A, Y)$, thus concealing Y_0 and Y_1 .

B.2 Identification

Let \mathbb{P}_0 be an experiment that generates $\mathbb{O} \doteq (W, Y_0, Y_1, A, Y)$. We think of W as the context where an action is undertaken, of Y_0 and Y_1 as the counterfactual (potential) rewards that actions $a = 0$ and $a = 1$ would entail, of A as the action carried out, and of Y as the reward received in response to action A . Consider the following assumptions:

1. **Randomization**: under \mathbb{P}_0 , the counterfactual rewards Y_0 , Y_1 and action A are conditionally independent given W , *i.e.*, $Y_a \perp A \mid W$ for $a = 0, 1$.
2. **Consistency**: under \mathbb{P}_0 , if action A is undertaken then reward Y_A is received, *i.e.*, $Y = Y_A$ (or $Y = Y_a$ given that $A = a$).

3. **Positivity:** under \mathbb{P}_0 , both actions $a = 0$ and $a = 1$ have (\mathbb{P}_0 -almost surely) a positive probability to be undertaken given W , i.e., $\Pr_{\mathbb{P}_0}(\ell\bar{G}_0(a, W) > 0) = 1$ for $a = 0, 1$.

Proposition B.1 (Identification). *Under the above assumptions, it holds that*

$$\psi_0 = E_{\mathbb{P}_0}(Y_1 - Y_0) = E_{\mathbb{P}_0}(Y_1) - E_{\mathbb{P}_0}(Y_0).$$

Proof. Set arbitrarily $a \in \{0, 1\}$. By the randomization assumption on the one hand (second equality) and by the consistency and positivity assumptions on the other hand (third equality), it holds that

$$\begin{aligned} E_{\mathbb{P}_0}(Y_a) &= \int E_{\mathbb{P}_0}(Y_a \mid W = w) dQ_{0,W}(w) = \int E_{\mathbb{P}_0}(Y_a \mid A = a, W = w) dQ_{0,W}(w) \\ &= \int E_{P_0}(Y \mid A = a, W = w) dQ_{0,W}(w) = \int \bar{Q}_0(a, W) dQ_{0,W}(w). \end{aligned}$$

The stated result easily follows. \square

Remark. The positivity assumption is needed for $E_{P_0}(Y \mid A = a, W) \doteq \bar{Q}_0(a, W)$ to be well-defined.

B.3 Building a confidence interval

Let Φ be the standard normal distribution function. Let X_1, \dots, X_n be independently drawn from a given law.

B.3.1 CLT & Slutsky's lemma

Assume that $\sigma^2 \doteq \text{Var}(X_1)$ is finite. Let $m \doteq E(X_1)$ be the mean of X_1 and $\bar{X}_n \doteq n^{-1} \sum_{i=1}^n X_i$ be the empirical mean. By the central limit theorem (CLT), it holds that $\sqrt{n}(\bar{X}_n - m)$ converges in law as n grows to the centered Gaussian law with variance σ^2 .

Moreover, if σ_n^2 is a (positive) consistent estimator of σ^2 then, by Slutsky's lemma, $\sqrt{n}/\sigma_n(\bar{X}_n - m)$ converges in law to the standard normal law. The empirical variance $n^{-1} \sum_{i=1}^n (X_i - \bar{X}_n)^2$ is such an estimator.

Proposition B.2. *Under the above assumptions,*

$$\left[\bar{X}_n \pm \Phi^{-1}(1 - \alpha) \frac{\sigma_n}{\sqrt{n}} \right]$$

is a confidence interval for m with asymptotic level $(1 - 2\alpha)$.

B.3.2 CLT and order statistics

Suppose that the law of X_1 admits a continuous distribution function F . Set $p \in]0, 1[$ and, assuming that n is large, find $k \geq 1$ and $l \geq 1$ such that

$$\frac{k}{n} \approx p - \Phi^{-1}(1 - \alpha) \sqrt{\frac{p(1-p)}{n}}$$

and

$$\frac{l}{n} \approx p + \Phi^{-1}(1 - \alpha) \sqrt{\frac{p(1-p)}{n}}.$$

Proposition B.3. *Under the above assumptions, $[X_{(k)}, X_{(l)}]$ is a confidence interval for $F^{-1}(p)$ with asymptotic level $1 - 2\alpha$.*

B.4 Another representation of the parameter of interest

For notational simplicity, note that $(2a - 1)$ equals 1 if $a = 1$ and -1 if $a = 0$. Now, for each $a = 0, 1$,

$$\begin{aligned} \mathbb{E}_{P_0} \left(\frac{\mathbf{1}\{A = a\}Y}{\ell \bar{G}_0(a, W)} \right) &= \mathbb{E}_{P_0} \left(\mathbb{E}_{P_0} \left(\frac{\mathbf{1}\{A = a\}Y}{\ell \bar{G}_0(a, W)} \middle| A, W \right) \right) \\ &= \mathbb{E}_{P_0} \left(\frac{\mathbf{1}\{A = a\}}{\ell \bar{G}_0(a, W)} \bar{Q}_0(A, W) \right) \\ &= \mathbb{E}_{P_0} \left(\frac{\mathbf{1}\{A = a\}}{\ell \bar{G}_0(a, W)} \bar{Q}_0(a, W) \right) \\ &= \mathbb{E}_{P_0} \left(\mathbb{E}_{P_0} \left(\frac{\mathbf{1}\{A = a\}}{\ell \bar{G}_0(a, W)} \bar{Q}_0(a, W) \middle| W \right) \right) \\ &= \mathbb{E}_{P_0} \left(\frac{\ell \bar{G}_0(a, W)}{\ell \bar{G}_0(a, W)} \bar{Q}_0(a, W) \middle| W \right) \\ &= \mathbb{E}_{P_0} (\bar{Q}_0(a, W)), \end{aligned}$$

where the first, fourth and sixth equalities follow from the tower rule¹, and the second and fifth hold by definition of the conditional expectation. This completes the proof.

B.5 The delta-method

Let f be a map from $\Theta \subset \mathbb{R}^p$ to \mathbb{R}^q that is differentiable at $\theta \in \Theta$. Let X_n be a random vector taking its values in Θ .

¹For any random variable (U, V) such that $\mathbb{E}(U|V)$ and $\mathbb{E}(U)$ are well defined, it holds that $\mathbb{E}(\mathbb{E}(U|V)) = \mathbb{E}(U)$.

Proposition B.4. *If $\sqrt{n}(X_n - \theta)$ converges in law to the Gaussian law with mean μ and covariance matrix Σ , then $\sqrt{n}(f(X_n) - f(\theta))$ converge in law to the Gaussian law with mean $\nabla f(\theta) \times \mu$ and covariance matrix $\nabla f(\theta) \times \Sigma \times \nabla f(\theta)^\top$. In addition, if Σ_n estimates Σ consistently then, by Slutsky's lemma, the asymptotic variance of $\sqrt{n}(f(X_n) - f(\theta))$ is consistently estimated with $\nabla f(X_n) \times \Sigma_n \times \nabla f(X_n)^\top$.*

B.6 The oracle logistic risk

First, let us recall the definition of the Kullback-Leibler divergence between Bernoulli laws of parameters $p, q \in]0, 1[$:

$$\text{KL}(p, q) \triangleq p \log \left(\frac{p}{q} \right) + (1 - p) \log \left(\frac{1 - p}{1 - q} \right).$$

It satisfies $\text{KL}(p, q) \geq 0$ where the equality holds if and only if $p = q$.

Let $f : [0, 1] \times \{0, 1\} \times [0, 1] \rightarrow [0, 1]$ be a (measurable) function. Applying the tower rule shows that the oracle logistic risk satisfies

$$\begin{aligned} \mathbb{E}_{P_0} (L_y(f)(O)) &= \mathbb{E}_{P_0} (-\bar{Q}_0(A, W) \log f(A, W) - (1 - \bar{Q}_0(A, W)) \log (1 - f(A, W))) \\ &= \mathbb{E}_{P_0} (\text{KL}(\bar{Q}_0(A, W), f(A, W))) + \text{constant}, \end{aligned} \tag{B.1}$$

where the above constant equals

$$-\mathbb{E}_{P_0} (\bar{Q}_0(A, W) \log \bar{Q}_0(A, W) - (1 - \bar{Q}_0(A, W)) \log (1 - \bar{Q}_0(A, W))).$$

In light of (B.1), \bar{Q}_0 minimizes $f \mapsto \mathbb{E}_{P_0} (L_y(f)(O))$ over the set of (measurable) functions mapping $[0, 1] \times \{0, 1\} \times [0, 1]$ to $[0, 1]$. Moreover, as an average of measures of discrepancy, $\mathbb{E}_{P_0} (L_y(f)(O))$ is also a measure of discrepancy.

Appendix C

More results and their proofs

C.1 Estimation of the asymptotic variance of an estimator

C.1.1 IPTW estimator based on a well-specified model

Sketch of proof. The IPTW estimator ψ_n^b relies on algorithm $\widehat{\mathcal{A}}_{\bar{G},1}$, which is “well-specified” in the sense that its output $\bar{G}_n \doteq \widehat{\mathcal{A}}_{\bar{G},1}(P_n)$ minimizes the empirical risk over a finite-dimensional, identifiable, well-specified working model for \bar{G}_0 . If one introduces D given by

$$D(O) \doteq \frac{(2A - 1)}{\ell_{\bar{G}_0}(A, W)} Y,$$

then the influence curve of ψ_n^b equals $D - \Psi(P_0)$ minus the projection of D onto the tangent space of the above parametric model for \bar{G}_0 . The variance of the influence curve is thus smaller than that of D , hence the conservativeness.

C.1.2 G-computation estimator based on a well-specified model

Sketch of proof (see [van der Laan and Rose, 2011] page 527). Consider a G-computation estimator ψ_n that relies on an algorithm $\widehat{\mathcal{A}}_{\bar{Q}}$ that is “well-specified” in the sense that its output $\bar{Q}_n \doteq \widehat{\mathcal{A}}_{\bar{Q}}(P_n)$ minimizes the empirical risk over a finite-dimensional, identifiable, well-specified working model for \bar{Q}_0 . If one introduces D given by

$$D(O) \doteq \bar{Q}_0(1, W) - \bar{Q}_0(0, W)$$

then the influence curve of ψ_n equals $D - \Psi(P_0)$ plus a function of O that is orthogonal to $D - \Psi(P_0)$. Thus the variance of the influence curve is larger than that of D , hence the anti-conservativeness.

C.2 2 General analysis of plug-in estimators

Recall that $\widehat{\mathcal{A}}_{Q_W}$ is an algorithm designed for the estimation of $Q_{0,W}$ (see Section 7.3) and that we denote by $Q_{n,W} \triangleq \widehat{\mathcal{A}}_{Q_W}(P_n)$ the output of the algorithm trained on P_n . Likewise, $\widehat{\mathcal{A}}_{\bar{G}}$ and $\widehat{\mathcal{A}}_{\bar{Q}}$ are two generic algorithms designed for the estimation of \bar{G}_0 and of \bar{Q}_0 (see Sections 7.4 and 7.6), $\bar{G}_n \triangleq \widehat{\mathcal{A}}_{\bar{G}}(P_n)$ and $\bar{Q}_n \triangleq \widehat{\mathcal{A}}_{\bar{Q}}(P_n)$ are their outputs once trained on P_n .

Let us now introduce P_n° a law in \mathcal{M} such that the Q_W , \bar{G} and \bar{Q} features of P_n° equal $Q_{n,W}$, \bar{G}_n and \bar{Q}_n , respectively. We say that any such law is *compatible* with $Q_{n,W}$, \bar{G}_n and \bar{Q}_n .

C.2.1 Main analysis

Substituting P_n° for P in (4.1) yields (9.1):

$$\sqrt{n}(\Psi(P_n^\circ) - \Psi(P_0)) = -\sqrt{n}P_0D^*(P_n^\circ) + \sqrt{n}\text{Rem}_{P_0}(P_n^\circ), \quad (\text{C.1})$$

an equality that we rewrite as

$$\sqrt{n}(\Psi(P_n^\circ) - \Psi(P_0)) = -\sqrt{n}P_nD^*(P_n^\circ) + \sqrt{n}(P_n - P_0)D^*(P_0) \quad (\text{C.2})$$

$$+ \sqrt{n}(P_n - P_0)[D^*(P_n^\circ) - D^*(P_0)] + \sqrt{n}\text{Rem}_{P_0}(P_n^\circ). \quad (\text{C.3})$$

Let us now study in turn the four terms in the above right-hand side sum. Recall that $X_n = o_{P_0}(1)$ means that $P_0(|X_n| > t)$ converges to zero for all $t > 0$ as n goes to infinity.

1. In view of (4.4), the fourth term is $o_{P_0}(1)$ provided that $\sqrt{n}\|\bar{Q} - \bar{Q}_0\|_{P_0} \times \|(\bar{G} - \bar{G}_0)/\ell\bar{G}_0\|_{P_0} = o_{P_0}(1)$. This is the case if, for instance, $\ell\bar{G}_0$ is bounded away from zero, and both $n^{1/4}\|\bar{Q} - \bar{Q}_0\|_{P_0}$ and $n^{1/4}\|\bar{G} - \bar{G}_0\|_{P_0}$ are $o_{P_0}(1)$. What really matters, remarkably, is the *product* of the two norms. If each norm goes to zero at rate $n^{1/4}$, then their product does at rate \sqrt{n} . Of course, if one goes to zero at rate $n^{1/4+c}$ for some $0 < c < 1/4$, then it suffices that the other go to zero at rate $n^{1/4-c}$. See also Section C.3.
2. A fundamental result from empirical processes theory gives us conditions guaranteeing that the third term is $o_{P_0}(1)$. By Lemma 19.24 in [van der Vaart, 1998], this is the case indeed if $\|D^*(P_n^\circ) - D^*(P_0)\|_{P_0} = o_{P_0}(1)$ (that is, if $D^*(P_n^\circ)$ estimates consistently $D^*(P_0)$) and if $D^*(P_n^\circ)$ falls (with probability tending to one) into a Donsker class

(meaning that the random $D^*(P_n^\circ)$ must belong eventually to a set that is not too large). Requesting that $\|D^*(P_n^\circ) - D^*(P_0)\|_{P_0} = o_{P_0}(1)$ is not much if one is already willing to assume that $n^{1/4}\|\bar{Q} - \bar{Q}_0\|_{P_0}$ and $n^{1/4}\|\bar{G} - \bar{G}_0\|_{P_0}$ are $o_{P_0}(1)$. Moreover, the second condition can be interpreted as a condition on the complexity/versatility of algorithms $\widehat{\mathcal{A}}_{\bar{G}}$ and $\widehat{\mathcal{A}}_{\bar{Q}}$.

3. By the central limit theorem, the second term converges in law to the centered Gaussian law with variance $P_0 D^*(P_0)^2$.
4. As for the first term, all we can say is that it is a potentially large (because of the \sqrt{n} renormalization factor) *bias term*.

C.2.2 Estimation of the asymptotic variance

Let us show now that, under the assumptions we made in Section C.2.1 and additional assumptions of similar nature, $P_n D^*(P_n^\circ)^2$ estimates consistently the asymptotic variance $P_0 D^*(P_0)^2$. The proof hinges again on a decomposition of the difference between the two quantities as a sum of three terms:

$$P_n D^*(P_n^\circ)^2 - P_0 D^*(P_0)^2 = (P_n - P_0) (D^*(P_n^\circ)^2 - D^*(P_0)^2) \quad (\text{C.4})$$

$$+ (P_n - P_0) D^*(P_0)^2 + P_0 (D^*(P_n^\circ)^2 - D^*(P_0)^2). \quad (\text{C.5})$$

We study the three terms in turn. Recall that $X_n = o_{P_0}(1/\sqrt{n})$ means that $P_0(\sqrt{n}|X_n| > t)$ converges to zero for all $t > 0$ as n goes to infinity.

1. In light of the study of the third term in Section C.2.1, if $\|D^*(P_n^\circ)^2 - D^*(P_0)^2\|_{P_0} = o_{P_0}(1)$ and if $D^*(P_n^\circ)^2$ falls (with probability tending to one) into a Donsker class, then the first term is $o_{P_0}(1/\sqrt{n})$. Furthermore, if $D^*(P_n^\circ)$ falls (with probability tending to one) into a Donsker class, an assumption we made earlier, then so does $D^*(P_n^\circ)^2$. In addition, if $\|D^*(P_n^\circ) - D^*(P_0)\|_{P_0} = o_{P_0}(1)$, another assumption we made earlier, and if there exists a constant $c > 0$ such that

$$\sup_{n \geq 1} \|D^*(P_n^\circ) + D^*(P_0)\|_\infty \leq c \quad (\text{C.6})$$

P_0 -almost surely, then $\|D^*(P_n^\circ)^2 - D^*(P_0)^2\|_{P_0} = o_{P_0}(1)$ too because

$$\|D^*(P_n^\circ)^2 - D^*(P_0)^2\|_{P_0} \leq c \|D^*(P_n^\circ) - D^*(P_0)\|_{P_0}. \quad (\text{C.7})$$

The existence of such a constant c is granted whenever $\ell \bar{G}_0$ and $\ell \bar{G}_n$ are bounded away from zero. Note that the condition on $\ell \bar{G}_n$ can be enforced by us through the specification of algorithm $\widehat{\mathcal{A}}_{\bar{G}}$.

2. By the central limit theorem, \sqrt{n} times the second term converges in law to the centered Gaussian law with variance $\text{Var}_{P_0}(D^*(P_0)(O)^2)$, which is finite whenever $\ell \bar{G}_0$ is bounded away from zero. By Theorem 2.4 in [van der Vaart, 1998], the second term is thus $O_{P_0}(1/\sqrt{n})$ hence $o_{P_0}(1)$.

3. Finally, under assumption (C.6), the absolute value of the third term is smaller than

$$cP_0|D^*(P_n^\circ) - D^*(P_0)| \leq c\|D^*(P_n^\circ) - D^*(P_0)\|_{P_0} = o_{P_0}(1), \quad (\text{C.8})$$

where the inequality follows from the Cauchy-Schwarz inequality.

In conclusion, $P_n D^*(P_n^\circ)^2 - P_0 D^*(P_0)^2 = o_{P_0}(1)$, hence the result.

C.3 Asymptotic negligibility of the remainder term

Recall that $\|f\|_P^2 \doteq E_P(f(O)^2)$ is the $L_2(P)$ -norm of f , a measurable function from \mathcal{O} to \mathbb{R} . Assume that for $a = 0, 1$, $\ell G_n(a, W) \geq \delta > 0$ $Q_{0,W}$ -almost everywhere.

The Cauchy-Schwarz inequality then implies that, for $a = 0, 1$,

$$\text{Rem}_{P_0}(P_n^\circ) \leq \frac{2}{\delta} \max_{a=0,1} (\|\bar{Q}_n(a, \cdot) - \bar{Q}_0(a, \cdot)\|_{P_0}) \times \|\bar{G}_n - \bar{G}_0\|_{P_0}.$$

Therefore, if for $a = 0, 1$,

$$\|\bar{Q}_n(a, \cdot) - \bar{Q}_0(a, \cdot)\|_{P_0} = o_{P_0}(n^{-1/4})$$

and

$$\|\bar{G}_n - \bar{G}_0\|_{P_0} = o_{P_0}(n^{-1/4}),$$

then

$$\text{Rem}_{P_0}(P_n^\circ) = o_{P_0}(n^{-1/2}).$$

C.4 Analysis of targeted estimators

C.4.1 A basic fact on the influence curve equation

Recall the definition of D_1^* (3.4). For *any* estimator \bar{Q}_n^* of \bar{Q}_0 and a law P_n^* that is compatible with \bar{Q}_n^* and $Q_{n,W}$, it holds that

$$\begin{aligned} P_n D_1^*(P_n^*) &= \frac{1}{n} \sum_{i=1}^n D_1^*(P_n^*)(O_i) \\ &= \frac{1}{n} \sum_{i=1}^n \left(\bar{Q}_n(1, W_i) - \bar{Q}_n(0, W_i) - \int (\bar{Q}_n(1, w) - \bar{Q}_n(0, w)) dQ_{n,W}(w) \right) \\ &= \frac{1}{n} \sum_{i=1}^n (\bar{Q}_n(1, W_i) - \bar{Q}_n(0, W_i)) - \frac{1}{n} \sum_{i=1}^n (\bar{Q}_n(1, W_i) - \bar{Q}_n(0, W_i)) = 0. \end{aligned}$$

C.4.2 Fluctuation of the regression function along the fluctuation of a law

Let us resume the discussion where we left it at the end of Section 3.3.1. Let \bar{Q} be the conditional mean of Y given (A, W) under P . Set arbitrarily $h \in H \setminus \{0\}$ and a measurable function $(w, a) \mapsto f(a, w)$ taking non-negative values. Applying repeatedly the tower rule yields the following equalities:

$$\begin{aligned} E_{P_h}(f(A, W)Y) &= E_P(f(A, W)Y(1 + hs(O))) \\ &= E_P(f(A, W)E_P(Y(1 + hs(O))|A, W)) \\ &= E_P(f(A, W)(\bar{Q}(A, W) + hE_P(Ys(O)|A, W))) \\ &= E_P\left(f(A, W)\frac{\bar{Q}(A, W) + hE_P(Ys(O)|A, W)}{1 + hE_P(s(O)|A, W)} \times (1 + hE_P(s(O)|A, W))\right). \end{aligned}$$

Now, (3.1) implies that the density of (A, W) under P_h equals $(1 + hE_P(s(O)|A, W))$ when it is evaluated at (A, W) . Therefore, the last inequality rewrites as

$$E_{P_h}(f(A, W)Y) = E_{P_h}\left(f(A, W)\frac{\bar{Q}(A, W) + hE_P(Ys(O)|A, W)}{1 + hE_P(s(O)|A, W)}\right).$$

Since this equality is valid for an arbitrary $(w, a) \mapsto f(a, w)$ with non-negative values, we can deduce from it that the conditional mean of Y given (A, W) under P_h equals

$$\frac{\bar{Q}(A, W) + hE_P(Ys(O)|A, W)}{1 + hE_P(s(O)|A, W)}.$$

C.4.3 Computing the score of a fluctuation of the regression function

Let us resume the discussion where we left it at the beginning of Section 10.2.2. Set $\alpha, \beta \in \mathbb{R}$. The derivative of $h \mapsto \text{expit}(\alpha + \beta h)$ evaluated at $h = 0$ satisfies

$$\frac{d}{dh} \text{expit}(\alpha + \beta h)|_{h=0} = \beta \text{expit}(\alpha)(1 - \text{expit}(\alpha)).$$

Therefore, for any $(w, a) \in [0, 1] \times \{0, 1\}$,

$$\begin{aligned} \frac{d}{dh} \bar{Q}_h(a, w)|_{h=0} &= \frac{2a - 1}{\ell \bar{G}(a, w)} \text{expit}(\logit(\bar{Q}(a, w))) [1 - \text{expit}(\logit(\bar{Q}(a, w)))] \\ &= \frac{2a - 1}{\ell \bar{G}(a, w)} \bar{Q}(a, w) (1 - \bar{Q}(a, w)). \end{aligned}$$

This justifies the last but one equality in (10.7).

Furthermore the same derivations that led to (10.7) also imply, *mutatis mutandis*, that

$$\frac{d}{dh} L_y(\bar{Q}_h)(O)|_{h=0} = \frac{2A-1}{\ell \bar{G}(A, W)} (Y - \bar{Q}(A, W)).$$

In this light, and in view of (3.2), we can think of $\mathcal{Q}(\bar{Q}, \bar{G})$ as a fluctuation of \bar{Q} in the direction of

$$(w, a, y) \mapsto \frac{2a-1}{\ell \bar{G}(a, w)} (y - \bar{Q}(a, w)).$$

Thus if $P \in \mathcal{M}$ is such that $E_P(Y|A, W) = \bar{Q}(A, W)$ and $P(A = 1|W) = \bar{G}(W)$, then we can also think of $\mathcal{Q}(\bar{Q}, \bar{G})$ as a fluctuation of \bar{Q} in the direction of the second component $D_2^*(P)$ of the efficient influence curve $D^*(P)$ of Ψ at P (3.4).

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