



# Asymptotic Properties of the Hill Estimator

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## Preface

Simulations were performed using computer resources within the Aalto University School of Science "Science-IT" project.

Otaniemi, 23.8.2018

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# Symbols and abbreviations

## Symbols

$x^* = \sup\{x : F(x) < 1\}$	the right endpoint of the distribution $F$
$\gamma$	extreme value index
$F^\leftarrow(y) = \inf\{x : F(x) \geq y\}$	left-continuous inverse
$U$	the left-continuous inverse of $\frac{1}{1-F}$
$\mathbb{1}(p) = \begin{cases} 1, & \text{if } p \text{ is true} \\ 0, & \text{otherwise} \end{cases}$	indicator function
$X_{i,n}$	$i$ :th order statistic
$\lambda$	Lebesgue measure
$\limsup A_n = \bigcap_{k=1}^{\infty} \bigcup_{n=k}^{\infty} A_n$	limit supremum of a sequence of sets $A_n$
$RV_\alpha$	the set of regularly varying functions with index $\alpha$
$D(G_\gamma)$	the maximum domain of attraction of $G_\gamma$
$f \sim g$	$\lim_{x \rightarrow \infty} f(x)/g(x) = 1$

## Abbreviations

cdf	cumulative distribution function
i.d.d.	independent and identically distributed
a.s.	almost surely

# 1 Introduction

Heavy-tailed distributions appear in many fields of science such as insurance and finance. For example the loss returns of a speculative asset or insurance are often heavy-tailed and in practice the focus is often on risk evaluation. One example of such data set is Danish fire insurance loss data [14] [17], while [16], [9] and [6] contain further examples.

Analyzing the tail is challenging since using classical methods, such as empirical quantiles, it is impossible to extrapolate beyond the available data. This motivates the use of Extreme Value Theory (EVT), that provides a rigorous mathematical framework to study extremes. EVT characterizes the behavior of the distribution's tail and tail estimation is often of high practical importance.

One of the possible estimators for extreme value index is the Hill estimator, which was introduced by Bruce Hill in 1975 [11] and remains one of the most used tail estimators for heavy-tailed distributions. In this article we will review asymptotic properties of the Hill estimator and particularly its consistency.

Regularly varying functions form the mathematical foundation for the heavy-tailed distributions and consequently they play an important role in the theory of the Hill estimator. We carefully review their properties in addition to consistency of the Hill estimator. We also examine consistency of the Hill estimator by performing Monte Carlo simulations. Results for asymptotic normality of the Hill estimator are provided but won't be discussed in detail.

The rest of the article is organized as follows. Section 2 gives requisites for the proofs and theory of the Hill estimator including properties of heavy tailed functions. Section 3 represents the main result, which is consistency and necessary lemmas for the proof of the consistency. Simulations are presented in Section 4 and concluding remarks are given in Section 5. Lastly, all the proofs and figures are found in Appendixes A and B.



## 2 Background

### 2.1 Fisher-Tippett-Gnedenko Theorem

Let  $X_1, X_2, \dots, X_n$  be i.i.d. random variables with a cdf  $F$ . Consider the sample maxima  $M_n = \max(X_1, X_2, \dots, X_n)$ . The limiting behavior of  $M_n$  is trivial: Since  $X_1, X_2, \dots, X_n$  are i.i.d.

$$\begin{aligned} P(\max(X_1, X_2, \dots, X_n) \leq x) &= P(X_1 \leq x, X_2 \leq x, \dots, X_n \leq x) \\ &= P(X_1 \leq x)P(X_2 \leq x) \dots P(X_n \leq x) = F^n(x). \end{aligned}$$

Now,

$$\lim_{n \rightarrow \infty} F^n(x) = \begin{cases} 0, & x < x^* \\ 1, & x \geq x^*. \end{cases}$$

To achieve a nondegenerate distribution it is necessary to normalize the sample maxima  $M_n$ . The Fisher-Tippett-Gnedenko Theorem states that with a suitable normalization a nondegenerate distribution is obtained [7], [8].

**Theorem 2.1.** *There exists real constants  $a_n > 0$  and  $b_n \in \mathbb{R}$  such that*

$$\lim_{n \rightarrow \infty} F^n(a_n x + b_n) = G_\gamma(ax + b), \quad (1)$$

where

$$G_\gamma(x) = \begin{cases} \exp(-(1 + \gamma x)^{-\frac{1}{\gamma}}), & \gamma \neq 0 \\ \exp(-e^{-x}), & \gamma = 0, \end{cases}$$

for all  $x$  with  $1 + \gamma x > 0$  where  $\gamma \in \mathbb{R}$ .

If  $F$  satisfies the equation 1 for some  $\gamma \in \mathbb{R}$  then it is said that  $F$  is in the maximum domain of attraction of  $G_\gamma$ , denoted  $F \in D(G_\gamma)$ .

We are especially interested in heavy-tailed distributions, i.e. the case  $F \in D(G_\gamma)$ , with  $\gamma > 0$ . It turns out that  $F$  being heavy-tailed is equivalent to the function  $1 - F$  being regularly varying with index  $-1/\gamma$ . In other words, if the tail function  $1 - F$  of a distribution is regularly varying then the distribution  $F$  is heavy tailed and vice versa. [9]

**Theorem 2.2.** *Cdf  $F$  is in the maximum domain of attraction of the extreme value distribution  $G_\gamma$  with  $\gamma > 0$  if and only if  $x^* = \infty$  and*

$$\lim_{t \rightarrow \infty} \frac{1 - F(tx)}{1 - F(t)} = x^{-\frac{1}{\gamma}}, x > 0. \quad (2)$$

In addition, condition (2) can be written in different form with the  $U$  function [9].

**Corollary 2.3.** *Condition 2 is equivalent to*

$$\lim_{t \rightarrow \infty} \frac{U(tx)}{U(t)} = x^\gamma, x > 0. \quad (3)$$

Relation (3) turns out to be easier to work with than (2) and thus it is used in further calculations.

## 2.2 Regularly Varying Functions

In Section 2.1 we saw that  $F \in D(G_\gamma)$  with  $\gamma > 0$  and  $U$  being regularly varying function are equivalent conditions. Regularly varying functions have some useful properties that are needed for the proof of the Hill estimator's consistency. Let's define regularly varying functions properly [9]:

**Definition 2.4.** *A Lebesgue measurable function  $f : \mathbb{R}^+ \rightarrow \mathbb{R}$  that is eventually positive is regularly varying if for some index  $\alpha \in \mathbb{R}$ ,*

$$\lim_{x \rightarrow \infty} \frac{f(tx)}{f(t)} = x^\alpha, \quad x > 0. \quad (4)$$

If a function  $f$  is regularly varying with index  $\alpha = 0$  then  $f$  is said to be slowly varying. One property of regularly varying functions is that all of them can be written in form  $f(x) = l(x)x^\alpha$  where  $l(x)$  is slowly varying function. This supports the intuition that heavy tailed distributions behave like pareto distribution after a high threshold.

**Theorem 2.5.** *If  $f \in RV_\alpha$  then the convergence in the equation 4 is uniform .*

$$\lim_{t \rightarrow \infty} \sup_{x \in [a, b]} \left| \frac{f(tx)}{f(t)} - x^\alpha \right| = 0,$$

for  $0 < a < b < \infty$ .

With uniform convergence it can be proved that all the regularly varying functions can be represented in certain form:

**Theorem 2.6** (Karamata's representation theorem). *If  $f \in RV_\alpha$  then there exists measurable functions  $a : \mathbb{R} \rightarrow \mathbb{R}^+$  and  $c : \mathbb{R} \rightarrow \mathbb{R}^+$  with*

$$\lim_{t \rightarrow \infty} c(t) = c_0 \text{ and } \lim_{t \rightarrow \infty} a(t) = \alpha$$

and  $t_0 \in \mathbb{R}^+$  such that for  $t > t_0$

$$f(t) = c(t) \exp \left( \int_{t_0}^t \frac{a(s)}{s} ds \right) \quad (5)$$

Conversely, if 2.6 holds, then  $f \in RV_\alpha$ .

For the proof of the above theorem following lemma about the integrals of the regularly varying functions is needed.

**Lemma 2.7.** *Suppose  $f \in RV_\alpha$ . There exists  $t_0 > 0$  such that  $f(t)$  is positive and locally bounded for  $t \geq t_0$ . If  $\alpha \geq -1$  then*

$$\lim_{t \rightarrow \infty} \frac{tf(t)}{\int_{t_0}^t f(s)ds} = \alpha + 1. \quad (6)$$

If  $\alpha < -1$  or  $\alpha = -1$  and  $\int_0^\infty f(s)ds < \infty$ , then

$$\lim_{t \rightarrow \infty} \frac{tf(t)}{\int_t^\infty f(s)ds} = -\alpha - 1. \quad (7)$$

Conversely, if 6 holds for  $-1 \leq \alpha < \infty$  or 7 holds for  $-\infty < \alpha < -1$ , then  $f \in RV_\alpha$ .

The following corollary of the Karamata's representation theorem will play a key role in the proof of the consistency of the Hill estimator.

**Corollary 2.8.** *Suppose  $f \in RV_\alpha$ . If  $\varepsilon, \delta > 0$  are arbitrary, there exists  $t_0 = t_0(\varepsilon, \delta)$  such that for  $t \geq t_0$ ,  $tx \geq t_0$ ,*

$$(1 - \varepsilon)x^{\alpha-\delta} < \frac{f(tx)}{f(t)} < (1 + \varepsilon)x^{\alpha+\delta}$$

### 3 Hill Estimator

The Hill estimator is defined as follows:

$$\hat{\gamma} = \frac{1}{k} \sum_{i=0}^{k-1} \log(X_{n-i,n}) - \log(X_{n-k,n}), \quad 1 \leq k \leq n-1$$

where  $k$  is a free parameter and  $X_{1,n} \leq X_{2,n} \leq \dots \leq X_{n,n}$  are order statistics. So essentially Hill estimator is mean of logarithm of distances between order statistics and the threshold  $X_{n-k,n}$ .

#### 3.1 Consistency

The following theorem states that Hill estimator is consistent i.e. estimator converges in probability to extreme value index. [11]

**Theorem 3.1.** *Let  $X_1, X_2, \dots$  be i.d.d. variables with cdf  $F_X$ . Suppose  $F_X \in D(G_\gamma)$  with  $\gamma > 0$ . Then as  $n \rightarrow \infty$ ,  $k = k(n) \rightarrow \infty$ ,  $k/n \rightarrow 0$ ,*

$$\hat{\gamma} \xrightarrow{P} \gamma.$$

For the proof of the above theorem following lemmas and corollary 2.8 are needed, firstly the Renyi's representation [15].

**Lemma 3.2.** *If  $E_1, E_2, \dots$  are i.d.d. random variables from the standard exponential distribution and  $E_{1,n} \leq E_{2,n} \leq \dots \leq E_{n,n}$  then for  $k \leq n$  we have*

$$(E_{1,n}, E_{2,n}, \dots, E_{k,n}) \stackrel{d}{=} \left( \frac{E_1^*}{n}, \frac{E_1^*}{n} + \frac{E_2^*}{n-1}, \dots, \frac{E_1^*}{n} + \frac{E_2^*}{n-1} + \dots + \frac{E_k^*}{n-k+1} \right),$$

where  $E_1^*, E_2^*, \dots$  are i.d.d. random variables from standard exponential distribution.

With Renyi's representation the complicated joint distribution of dependent order statistics can be represented in terms of independent random variables. Proof of the Renyi's representation is omitted here.

Secondly a lemma about the order statistics of Pareto distribution is necessary [9].

**Lemma 3.3.** *Let  $Y_1, Y_2, \dots$  be i.d.d. random variables from Pareto distribution  $F_Y(y) = 1 - \frac{1}{y}$ ,  $y \geq 0$  and let  $Y_{1,n} \geq Y_{2,n} \geq \dots \geq Y_{n,n}$  be the  $n$ th order statistics. Then with such  $k = k(n)$  that  $k \rightarrow \infty$ ,  $\frac{k}{n} \rightarrow 0$  as  $n \rightarrow \infty$ ,*

$$\lim_{n \rightarrow \infty} Y_{n-k,n} = \infty \quad a.s.$$

Finally we need the fact that  $U(Y)$  is equal in distribution to  $X$ , where  $Y$  is random variable from Pareto distribution and  $X$  is random variable from some distribution  $F_X$ .

**Lemma 3.4.** *Let  $Y$  be random variable from Pareto distribution  $F_Y = 1 - \frac{1}{y}$ ,  $y \geq 0$ . Let  $X$  be random variable with cdf  $F_X$  then  $U(Y) \stackrel{d}{=} X$ .*

Notably, there is also converse version of the theorem 3.1 [13]. Proof is omitted here.

**Theorem 3.5.** *Let  $X_1, X_2, \dots$  be i.i.d. variables from cdf  $F$ . Suppose that for some sequence of integers  $k = k(n) \rightarrow \infty$ ,  $k(n)/n \rightarrow 0$  and  $k(n+1)/k(n) \rightarrow 1$  as  $n \rightarrow \infty$*

$$\hat{\gamma}_H \rightarrow \gamma > 0.$$

*Then  $F \in D(G_\gamma)$*

The almost sure convergence of the Hill estimator is also proved in [13].

## 3.2 Asymptotic Normality

In addition to the first-order regular variation 2.4 there is a second-order condition for regular variation, which allows to examine the rates of converge of the first-order condition. Second-order regular variation is needed for the asymptotic normality of Hill estimator. We define second-order regular variation for case  $\gamma > 0$ , since it is sufficient for our purposes.

**Definition 3.6.**  *$f$  is second-order regularly varying function for parameters  $\gamma > 0$  and  $\rho \leq 0$  if for  $x > 0$*

$$\lim_{t \rightarrow \infty} \frac{\frac{f(tx)}{f(t)} - x^\gamma}{A(t)} = x^\gamma \frac{x^\rho - 1}{\rho},$$

*where  $A$  is a one-signed function with  $\lim_{t \rightarrow \infty} A(t) = 0$ , with the right-hand side interpreted as  $x^\gamma \log x$  for  $\rho = 0$ .*

The asymptotic normality of  $\hat{\gamma}$  can be formulated using the second-order condition [2].

**Theorem 3.7.** *Suppose that cdf  $F$  satisfies the second-order condition 3.6 and  $k = k(n)$  with  $k(n) \rightarrow \infty$ ,  $k(n)/n \rightarrow \infty$  when  $n \rightarrow \infty$ . Then*

$$\sqrt{k}(\hat{\gamma} - \gamma) \xrightarrow{d} N\left(\frac{\lambda}{1 - \rho}, \gamma^2\right)$$

*where*

$$\lim_{t \rightarrow \infty} \sqrt{k} A\left(\frac{n}{k}\right) = \lambda, \quad \lambda \in \mathbb{R}.$$

From theorem 3.7 it can be seen that for Hill estimator to be asymptotically normal  $U$  of the distribution has to satisfy the second-order regular variation. Furthermore, there is an asymptotic bias that depends on the second-order parameter  $\rho$  and  $\lambda$ .

## 4 Simulations

The consistency of the Hill estimator is studied with a Monte Carlo simulation. We simulate observations from the Pareto distribution with an extreme value index  $\gamma = 1/3$  and Cauchy distribution ( $\gamma = 1$ , as can be checked with equation 2 or 3). We simulate  $N = 2000$  sets of  $n_i$  observations from both distributions where  $n_i = 100 + 50(i - 1)$ ,  $i = 1, 2, \dots, 399$ . Hence the sample size is a vector from 100 to 20000 with steps of 50. We denote this vector with  $\mathbf{n} = (100, 150, \dots, 20000)$ . So for each  $n_i$  we calculate  $N$  number of estimates  $\hat{\gamma}$  with  $k = k(n) = o(n)$ . For  $k$  we chose  $k(n) = \sqrt{n}$ , thus the condition  $k = o(n)$  is fulfilled. Results are shown in figures B.1 and B.2. Below is a summary of simulation settings.

Table 1: Simulation settings.

Figure	Distribution	$\gamma$	Estimator	$n$	$N$	$k(n)$
B.1	Pareto	1/3	Hill	$\mathbf{n}$	2000	$\sqrt{n}$
B.2	Cauchy	1	Hill	$\mathbf{n}$	2000	$\sqrt{n}$

Both resulting graphs are constructed in the same manner. Real value of the extreme value index  $\gamma$  is plotted as a dashed line. Black curve represents the medians, red curve 1st quartiles and blue curve 3rd quartiles of the  $N$  sized samples of estimates.

In figure B.1 it seems that with small  $n$  convergence is very fast and slows down after a while. This can be seen by looking at the quartiles. At the beginning the quartiles squeeze around  $\gamma$  but eventually after about  $n = 12500$  it is hard to see any further convergence.

In figure B.2 we can conclude that convergence is fast with small numbers of observations but slows down eventually, as in figure B.1. It seems that the median is a little further from  $\gamma$  than in figure B.1. This suggests that for Cauchy distribution larger sample size is needed for an accurate estimate for  $\gamma$  than for Pareto distribution. In both figures B.1 and B.2 quartiles are equally far away from median which suggests that asymptotical distribution of Hill estimator might be symmetrical.

## 5 Conclusion

We reviewed the proof of the Hill estimator's consistency. Properties of the regularly varying functions played a crucial role in the proof of the consistency. Consistency was also studied with simulations, which also showed that Hill estimator has good finite sample properties. Other properties of the Hill estimator such as asymptotic normality and bias are not in the scope of this article. However, these properties are studied in other articles such as [2], [10] and [3].

Finally, we note that the Hill estimator can be extended in various ways. For example, there are estimators similar to Hill estimator for the general case  $\gamma \in \mathbb{R}$ . Examples of these estimators include the Pickands estimator [12] and the Moment estimator [4]. The Hill estimator can also be extended to the multivariate case [5].

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## A Proofs

### A.1 Proof of Theorem 2.5

*Proof.* For a slowly varying function the limit relation 4 can be written in different form with function  $F = \log f(e^x)$ :

$$\lim_{t \rightarrow \infty} F(t+x) - F(x) = 0. \quad (\text{A1})$$

The above argument is true, since

$$F(t+x) - F(t) = \log f(e^{t+x}) - \log f(e^t) = \log \left( \underbrace{\frac{f(e^t e^x)}{f(e^t)}}_{\rightarrow 1} \right) \rightarrow 0$$

as  $t \rightarrow \infty$ . The alternative form for slow variation A1 is used in the proof of the uniform convergence.

For the proof it can be assumed that  $\alpha = 0$ . If this isn't the case replace  $f(x)$  by  $f(x)x^{-\alpha}$ . Suppose there exists sequences  $t_n \rightarrow \infty$ ,  $x_n \rightarrow 0$  as  $n \rightarrow \infty$  such that

$$\left| \frac{f(t_n x_n)}{f(t_n)} - 1 \right| > \delta$$

for all  $n \in \mathbb{N}$  and some  $\delta > 0$ . An equivalent condition can be formulated with function  $F(x) = \log f(e^x)$  (see equation A1):

$$|F(t_n + x_n) - F(t_n)| > \delta \quad (\text{A2})$$

with possibly different  $x_n$ ,  $t_n$  and  $\delta$ . Let's define sets

$$\begin{aligned} Y_{1,n} &= \left\{ y \in J : |F(t_n + y) - F(t_n)| > \frac{\delta}{2} \right\}, \\ Y_{2,n} &= \left\{ y \in J : |F(t_n + x_n) - F(t_n + y)| > \frac{\delta}{2} \right\} \quad \text{and} \\ Z_n &= \left\{ z : |F(t_n + x_n) - F(t_n + x_n - z)| > \frac{\delta}{2}, x_n - z \in J \right\} \\ &= \{z : x_n - z \in Y_{2,n}\} \end{aligned}$$

where  $J \subset \mathbb{R}$  is a finite interval. Next we will prove that if the equation A2 holds then pointwise convergence  $\lim_{t \rightarrow \infty} F(t + x_0) - F(t) = 0$  cannot hold. Pointwise convergence does not hold if some  $x_0$  is included in infinitely many  $Y_{1,n}$ . Reason for this is that

$$n \geq n_\varepsilon \Rightarrow |F(t + x_0) - F(t)| < \varepsilon, \forall \varepsilon > 0, \exists n_\varepsilon \in \mathbb{N} \quad (\text{A3})$$

cannot hold if  $x_0$  is included in infinitely many  $Y_{1,n}$ . This can be noticed by comparing equation A3 and the condition of  $Y_{1,n}$ . Similarly if  $x_0$  is included in infinitely many  $Z_n$  then pointwise convergence cannot hold, since the condition in  $Z_n$  can be written as

$$\begin{aligned} \left| F(\underbrace{t_n + x_n}_{=u_n}) - F(\underbrace{t_n + x_n}_{=u_n} \overset{=x_0}{-z}) \right| &> \frac{\delta}{2} \\ \Leftrightarrow |F(u_n + x_0) - F(u_n)| &> \frac{\delta}{2} \end{aligned}$$

where  $u_n \rightarrow \infty$ .

Notice that  $Y_{1,n} \cup Y_{2,n} = J$ , since by the equation A2 and triangle inequality we have

$$\begin{aligned} \delta &< |F(t_n + x_n) - F(t_n)| = |(F(t_n + x_n) - F(t_n + y)) + (F(t_n + y) - F(t_n))| \\ &\leq |(F(t_n + x_n) - F(t_n + y))| + |(F(t_n + y) - F(t_n))| \\ \Rightarrow |(F(t_n + x_n) - F(t_n + y))| &> \frac{\delta}{2} \vee |(F(t_n + y) - F(t_n))| > \frac{\delta}{2}. \end{aligned}$$

Additionally  $Y_{1,n}$ ,  $Y_{2,n}$  and  $J$  are measurable sets. So by subadditivity of the Lebesgue measure we have  $\lambda(Y_{1,n}) \geq \frac{\lambda(J)}{2} \vee \lambda(Y_{2,n}) \geq \frac{\lambda(J)}{2}$ . By the translation property of the Lebesgue measure  $\lambda(Z_n) = \lambda(Y_{2,n})$  holds. Thus  $\lambda(Y_{1,n}) \geq \frac{\lambda(J)}{2} \vee \lambda(Z_n) \geq \frac{\lambda(J)}{2}$  infinitely often. All  $Y_{1,n}$  are subsets of finite interval since  $Y_{1,n} \subset J$  for all  $n$ . Similarly all  $Z_n$  are subset of a finite interval since  $x_n \rightarrow 0$ . Hence by Fatou's lemma [1]:

$$\begin{aligned} \lambda(\limsup Y_{1,n}) &\geq \limsup \lambda(Y_{1,n}) \geq \frac{\lambda(J)}{2} \vee \\ \lambda(\limsup Z_n) &\geq \limsup \lambda(Z_n) \geq \frac{\lambda(J)}{2}. \end{aligned}$$

Since at least one of the measures  $\lambda(\limsup Y_{1,n})$  or  $\lambda(\limsup Z_n)$  is greater than zero, we have some  $x_0$  that is contained in infinitely many  $Y_{1,n}$  or  $Z_n$ . This was the desired contradiction.  $\square$

## A.2 Proof of Lemma 2.7

*Proof.* First we prove the equation 6. Suppose that  $f \in RV_\alpha$ . Then by theorem 2.5 there exists  $t_0$  and  $c$  such that  $f(tx)/t < c$  when  $t \geq t_0$ ,  $x \in [1, 2]$ . Then for  $t \in [2^n t_0, 2^{n+1} t_0]$  we have

$$\frac{f(t)}{f(t_0)} = \frac{f(t)}{f(2^{-1}t)} \frac{f(2^{-1}t)}{f(2^{-2}t)} \cdots \frac{f(2^{-n}t)}{f(t_0)} < c^{n+1}. \quad (\text{A4})$$

Equation A4 is true since every fraction can be written as  $f(tx)/f(t)$ . This implies that for  $t \geq t_0$   $f(t)$  is both locally bounded and  $\int_{t_0}^t f(s)ds < \infty$ . Consider a function

$F(t) = \int_{t_0}^t f(s)ds$ . We start by proving that  $\lim_{t \rightarrow \infty} F(t) = \infty$  when  $\alpha > -1$ . First notice that  $f(2s) \geq 2^{-1}f(s)$  for sufficiently large  $s$ . For  $n \geq n_0$

$$\int_{2^n}^{2^{n+1}} f(s)ds = 2 \int_{2^{n-1}}^{2^n} f(2s)ds \geq \int_{2^{n-1}}^{2^n} f(s)ds \quad (\text{A5})$$

by the change on variables. Then by induction we have

$$\int_{2^n}^{2^{n+1}} f(s)ds \geq \int_{2^{n_0}}^{2^{n_0+1}} f(s)ds = C > 0. \quad (\text{A6})$$

Thus

$$\int_{2^{n_0}}^{\infty} f(s)ds = \sum_{n=n_0}^{\infty} \int_{2^n}^{2^{n+1}} f(s)ds \geq \sum_{n=n_0}^{\infty} \int_{2^n}^{2^{n_0+1}} f(s)ds = \sum_{n=n_0}^{\infty} C = \infty \quad (\text{A7})$$

Next we prove that  $F \in RV_{\alpha+1}$  for  $\alpha > -1$ . Let  $\varepsilon > 0$  and  $t_1 = t_1(\varepsilon)$ . Then  $f(xt) < (1 + \varepsilon)x^\alpha f(t)$  for  $t > t_1$ . Since  $\lim_{t \rightarrow \infty} F(t) = \infty$ ,

$$\frac{F(tx)}{F(t)} = \frac{\int_{t_0}^{tx} f(s)ds}{\int_{t_0}^t f(s)ds} \sim \frac{\int_{t_1}^{tx} f(s)ds}{\int_{t_1}^t f(s)ds} = \frac{x \int_{t_1}^t f(xs)ds}{\int_{t_1}^t f(t)ds} < \frac{x \int_{t_1}^t (1 + \varepsilon)x^\alpha f(s)ds}{\int_{t_1}^t f(t)ds} = (1 + \varepsilon)x^{\alpha+1}$$

by the change of variables. A similar lower bound for  $F(tx)/F(t)$  can be derived by using  $f(xt) < (1 - \varepsilon)x^\alpha f(t)$  as  $t > t_1$ . So we have that  $F \in RV_{\alpha+1}$  for  $\alpha > -1$ . In the case  $\alpha = -1$  and  $F(t) \rightarrow \infty$  same proof applies. If  $\alpha = -1$  and  $F(t)$  has a finite limit and  $F \in RV_0$ . Now for all  $\alpha$

$$\begin{aligned} \frac{F(xt) - F(t)}{tf(t)} &= \frac{1}{tf(t)} \int_t^{tx} f(u)du = \frac{t}{tf(t)} \int_1^x f(ut)du = \int_1^x \frac{f(ut)}{f(t)} du \\ &\rightarrow \int_1^x u^\alpha du = \frac{x^{\alpha+1} - 1}{\alpha + 1}, \quad t \rightarrow \infty \end{aligned}$$

by the theorem 2.5 and change of variables. On the other hand

$$\begin{aligned} \frac{F(xt) - F(t)}{tf(t)} &= \frac{F(t)}{tf(t)} \left( \underbrace{\frac{F(tx)}{F(t)}}_{\rightarrow x^{\alpha+1}} - 1 \right) \rightarrow \frac{x^{\alpha+1} - 1}{\alpha + 1} \\ &\Rightarrow \lim_{t \rightarrow \infty} \frac{tf(t)}{F(t)} = \alpha + 1 \end{aligned}$$

Now we have proven 6. Next we prove equation 7. Let's define

$$G(t) = \int_t^{\infty} f(s)ds$$

In the case  $\alpha < -1$  there exists  $\delta > 0$  such that  $f(2s) \leq 2^{-1-\delta}f(s)$  for sufficiently large  $s$ . Now we can prove the finiteness of  $\lim_{t \rightarrow \infty} G(t)$  in a similar way as the infiniteness of  $\lim_{t \rightarrow \infty} F(t)$  in equations A5, A6 and A7. For sufficiently large  $n_1$

$$\begin{aligned} \int_{2^n}^{2^{n+1}} f(s)ds &= 2 \int_{2^{n-1}}^{2^n} f(s)ds \leq 2^{-\delta} \int_{2^{n-1}}^{2^n} f(s)ds \leq \\ &\dots \leq 2^{-\delta(n-n_1)} \int_{2^{n_1}}^{2^{n_1+1}} f(s)ds = 2^{-\delta(n-n_1)} C' \end{aligned}$$

by induction and change of variables. Then

$$\begin{aligned} \int_{2^{n_1}}^{\infty} f(s)ds &= \sum_{n=n_1}^{\infty} \int_{2^n}^{2^{n+1}} f(s)ds \leq C' \sum_{n=n_1}^{\infty} 2^{-\delta(n-n_1)} \\ &= C' \sum_{k=0}^{\infty} \left(\frac{1}{2^\delta}\right)^k = \frac{C'}{1-1/2^\delta} < \infty, \end{aligned}$$

Now rest of the proof is analogous. Next we prove the converse results. Suppose that equation 6 holds. Let's define a function

$$b(t) = t \frac{f(t)}{F(t)}$$

Without loss of generality we may suppose that  $f(t) > 0$  and  $t > 0$ . Integrating both sides of  $b(t)/t = f(t)/F(t)$  we obtain for some real  $c_1$  and for all  $x > 0$

$$\int_1^x \frac{b(t)}{t} dt = \log F(x) + c_1, \quad (\text{A8})$$

since by change of variables

$$\int_1^x \frac{f(t)}{F(t)} dt = \int_{F(1)}^{F(x)} \frac{1}{u} du = \log F(x) + \underbrace{\log F(1)}_{=c_1}.$$

From the equation A8 we have

$$F(t) = \exp \left( \int_1^x \frac{b(t)}{t} dt - c_1 \right) = \underbrace{\exp(-c_1)}_{=c} \exp \left( \int_1^x \frac{b(t)}{t} dt \right) = c \exp \left( \int_1^x \frac{b(t)}{t} dt \right).$$

Then by using the definition of  $f$  again

$$\begin{aligned} f(x) &= x^{-1} b(x) F(x) = c b(x) \exp \left( - \int_1^x \frac{1}{t} \right) \exp \left( \int_1^x \frac{b(t)}{t} \right) \\ &= c b(x) \exp \left( \int_1^x \frac{b(t) - 1}{t} dt \right), \end{aligned} \quad (\text{A9})$$

for all  $x > 0$ . Hence for all  $x, t > 0$

$$\begin{aligned} \frac{f(tx)}{f(t)} &= \frac{b(tx) \exp \left( \int_1^{tx} \frac{b(s)-1}{s} ds \right)}{b(t) \exp \left( \int_1^t \frac{b(s)-1}{s} ds \right)} = \frac{b(tx)}{b(t)} \exp \left( \int_1^{tx} \frac{b(s)-1}{s} ds - \int_1^t \frac{b(s)-1}{s} ds \right) \\ &= \frac{b(tx)}{b(t)} \exp \left( \int_t^{tx} \frac{b(s)-1}{s} ds \right) = \frac{b(tx)}{b(t)} \exp \left( \int_1^x \frac{b(ts)-1}{s} ds \right), \end{aligned}$$

by the change of variables. By the assumption (equation 6)  $b(t) \rightarrow \alpha + 1$  so  $b(tx)/b(t) \rightarrow 1$ . For sufficiently large  $t$

$$\exp \left( \int_1^x \frac{b(ts)-1}{s} ds \right) \approx \exp \left( \int_1^x \frac{\alpha}{s} ds \right) = \exp(\alpha \log x) = x^\alpha$$

The last statement (equation 7 implies that  $F \in RV_\alpha$ ) can be proved in a similar way.  $\square$

### A.3 Proof of Theorem 2.6

*Proof.* Suppose  $f \in RV_\alpha$ . The function  $t^{-\alpha}f(t)$  is slowly varying and

$$t^{-\alpha}f(t) = cb(t) \exp \left( \int_1^t \frac{b(s) - 1}{s} ds \right)$$

by the equation A9. Now by lemma 2.7  $b(t) \rightarrow 1$  and function  $t^{-\alpha}f(t)$  has the representation as in theorem 2.6 with  $a(t) = b(t) - 1$  and  $c(t) = cb(t)$ . Then

$$f(t) = c(t)t^\alpha \exp \left( \int_{t_0}^t \frac{a(s)}{s} ds \right)$$

Notice that we can write  $t^\alpha$  as  $\exp \left( \int_1^t \frac{\alpha}{s} ds \right)$ . Then  $f$  has the form

$$\begin{aligned} f(t) &= c(t) \exp \left( \int_{t_0}^t \frac{a(s)}{s} ds + \int_1^t \frac{\alpha}{s} ds \right) \\ &= c(t) \exp \left( \int_{t_0}^t \frac{a(s) + \alpha}{s} ds + \int_1^{t_0} \frac{\alpha}{s} ds \right) \\ &= c(t) \exp \left( \int_{t_0}^t \frac{a(s) + \alpha}{s} ds \right) \exp(\log t_0^\alpha) \\ &= \underbrace{t_0^\alpha c(t)}_{=c'} \exp \left( \int_{t_0}^t \overbrace{\frac{a(s) + \alpha}{s}}^{=a'} ds \right) \end{aligned} \tag{A10}$$

From the equation A10 it can be seen that  $f(t)$  has the same representation as in the theorem 2.6 when  $a$  is replaced by  $a'$  and  $c$  is replaced by  $c'$ .  $\square$

### A.4 Proof of Corollary 2.8

*Proof.* By the theorem 2.6

$$\frac{f(tx)}{f(t)} = \frac{c(tx)}{c(t)} \exp \left( \int_1^x \frac{a(st)}{s} ds \right)$$

The function  $c(t)$  converges to a constant. Hence  $c \in RV_0$  so  $c(tx)/c(t) \rightarrow 1$  as  $t \rightarrow \infty$ . Furthermore,  $a(s) \rightarrow \alpha$  as  $t \rightarrow \infty$ . Now we can choose such a  $t_0$  that  $\alpha - \delta < a(st) < \alpha + \delta$  and  $1 - \varepsilon < \frac{c(tx)}{c(t)} < 1 + \varepsilon$ . This implies that

$$\begin{aligned} (1 - \varepsilon) \int_1^x \frac{\alpha - \delta}{s} ds &< \frac{f(tx)}{f(t)} < (1 + \varepsilon) \int_1^x \frac{\alpha + \delta}{s} ds \\ \Rightarrow (1 - \varepsilon) \exp \left( \log \left( x^{\alpha - \delta} \right) \right) &< \frac{f(tx)}{f(t)} < (1 + \varepsilon) \exp \left( \log \left( x^{\alpha + \delta} \right) \right) \\ \Rightarrow (1 - \varepsilon) x^{\alpha - \delta} &< \frac{f(tx)}{f(t)} < (1 + \varepsilon) x^{\alpha + \delta} \end{aligned}$$

$\square$

### A.5 Proof of Lemma 3.3

*Proof.* Let us assume that  $Y_{n-k,n} < r$  for some  $r > 0$  infinitely often. In other words

$$\frac{k}{n} = \frac{1}{n} \sum_{i=1}^n \mathbb{1}(Y_i > Y_{n-k,n}) > \frac{1}{n} \sum_{i=1}^n \mathbb{1}(Y_i > r).$$

Now the left side of the equation converges to zero, since

$$\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n \mathbb{1}(Y_i > Y_{n-k,n}) = \lim_{n \rightarrow \infty} \frac{k}{n} = 0.$$

But the right side converges to  $1/r$  almost surely, since

$$\frac{1}{n} \sum_{i=1}^n \mathbb{1}(Y_i > r) \xrightarrow{a.s.} P(Y_i > r) = 1 - F_Y(r) = \frac{1}{r}$$

by the strong law of large numbers [18]. So the assumption cannot hold which implies that

$$P(\lim_{n \rightarrow \infty} Y_{n-k,n} = \infty) = 1.$$

□

### A.6 Proof of Lemma 3.4

*Proof.* Let's study the condition  $U(Y) \leq a, a \in \mathbb{R}$ .

$$\begin{aligned} U(Y) &\leq a \\ \Leftrightarrow \inf \left\{ x : \frac{1}{1 - F_X(x)} \geq Y \right\} &\leq a \\ \Leftrightarrow \inf \left\{ x : 1 - \frac{1}{Y} \leq F_X(x) \right\} &\leq a \end{aligned} \tag{A11}$$

Let  $S = \left\{ x : 1 - \frac{1}{Y} \leq F_X(x) \right\}$  and  $b = \inf S$ . Notice that  $F$  is increasing and right-continuous, since  $F$  is a cdf. So  $S$  is an interval of form  $[b, \infty)$  or  $(b, \infty)$ , since  $F$  is increasing. Let's define a sequence  $x_n = b + \frac{1}{n}, n \in \mathbb{N}$ . Notice that  $x_n \rightarrow b$  and  $x_n \in S$  for all  $n$ . Now right-continuity implies that  $b \in S$  i.e  $S$  is an interval  $[b, \infty)$ . Additionally  $a \in S$  since  $a \geq b$  so  $a$  satisfies the condition  $1 - \frac{1}{Y} \leq F(a)$ . Therefore the equation A11 implies

$$U(Y) \leq a \Leftrightarrow 1 - \frac{1}{Y} \leq F_X(a) \Leftrightarrow Y \leq \frac{1}{1 - F(a)},$$

So now from the cdf of  $U(Y)$  we have

$$\begin{aligned} F_{U(Y)} &= P(U(Y) \leq x) = P\left(Y \leq \frac{1}{1 - F_X(x)}\right) = F_Y\left(\frac{1}{1 - F_X(x)}\right) \\ &= 1 - \left(\frac{1}{1 - F_X(x)}\right)^{-1} = F_X(x). \end{aligned}$$

□

## A.7 Proof of Theorem 3.1

*Proof.*  $F \in D(G_{\gamma>0})$  is equivalent to the fact that  $U \in RV_\gamma$  i.e.

$$\lim_{t \rightarrow \infty} \frac{U(tx)}{U(t)} = x^\gamma.$$

From the uniform convergence of the regularly varying functions follows that for  $x > 1$  and  $t \geq t_0$ ,

$$(1 - \varepsilon)x^{\gamma-\delta} < \frac{U(tx)}{U(t)} < (1 + \varepsilon)x^{\gamma+\delta},$$

for all  $\varepsilon > 0$  and  $\delta > 0$ . By taking natural logarithm from both sides of the equation above, it can be written as

$$\begin{aligned} \log(1 - \varepsilon) + (\gamma - \delta) \log(x) &< \log(U(tx)) - \log(U(t)) \\ &< \log(1 + \varepsilon) + (\gamma + \delta) \log(x). \end{aligned} \quad (\text{A12})$$

If  $Y_1, Y_2, \dots$  are i.i.d random variables from Pareto distribution with cdf  $F_Y(y) = 1 - \frac{1}{y}$  then  $U(Y_i) \stackrel{d}{=} X_i$  as stated in lemma 3.4. Hence it is sufficient to prove the result for  $\hat{\gamma}_H = \frac{1}{k} \sum_{i=0}^{k-1} \log(U(Y_{n-i,n})) - \log(U(Y_{n-k,n}))$ . For  $t = Y_{n-k,n}$  and  $x = \frac{Y_{n-i,n}}{Y_{n-k,n}}$  equation A12 has the form

$$\begin{aligned} \log(1 - \varepsilon) + (\gamma - \delta) \log\left(\frac{Y_{n-i,n}}{Y_{n-k,n}}\right) &< \log(U(Y_{n-i,n})) - \log(U(Y_{n-k,n})) \\ &< \log(1 + \varepsilon) + (\gamma + \delta) \log\left(\frac{Y_{n-i,n}}{Y_{n-k,n}}\right). \end{aligned} \quad (\text{A13})$$

Notice that we can replace  $t$  with  $Y_{n-k,n}$  because we can always find some  $n_0$  such that  $Y_{n_0-k,n_0} \geq t_0$  according to lemma 3.3. Furthermore,  $Y_{n-i,n}$  is greater than  $Y_{n-k,n}$  always when  $i < k$ . Therefore  $x$  can be replaced with  $\frac{Y_{n-i,n}}{Y_{n-k,n}}$ .

Equation A13 applies for every  $i = 0, 1, 2, \dots, k-1$ . Thus we can write

$$\begin{aligned} \log(1 - \varepsilon) + (\gamma - \delta) \frac{1}{k} \sum_{i=0}^{k-1} \log\left(\frac{Y_{n-i,n}}{Y_{n-k,n}}\right) &< \frac{1}{k} \sum_{i=0}^{k-1} \log(U(Y_{n-i,n})) - \log(U(Y_{n-k,n})) \\ &< \log(1 + \varepsilon) + (\gamma + \delta) \frac{1}{k} \sum_{i=0}^{k-1} \log\left(\frac{Y_{n-i,n}}{Y_{n-k,n}}\right). \end{aligned}$$

The term in the middle is the hill estimator  $\hat{\gamma}_H$ , hence above becomes

$$\begin{aligned} \log(1 - \varepsilon) + (\gamma - \delta) \frac{1}{k} \sum_{i=0}^{k-1} \log\left(\frac{Y_{n-i,n}}{Y_{n-k,n}}\right) &< \hat{\gamma}_H \\ &< \log(1 + \varepsilon) + (\gamma + \delta) \frac{1}{k} \sum_{i=0}^{k-1} \log\left(\frac{Y_{n-i,n}}{Y_{n-k,n}}\right). \end{aligned}$$



Now it is sufficient to only prove that

$$\frac{1}{k} \sum_{i=0}^{k-1} \log \left( \frac{Y_{n-i,n}}{Y_{n-k,n}} \right) \xrightarrow{p} 1.$$

$\log(Y_i)$  has a standard exponential distribution, since

$$F_{\log(Y_i)}(x) = P(\log(Y_i) < x) = P(e^{\log(Y_i)} < e^x) = P(Y_i < e^x) = F_Y(e^x) = 1 - e^{-x}.$$

Therefore we can write

$$\frac{1}{k} \sum_{i=0}^{k-1} \log \left( \frac{Y_{n-i,n}}{Y_{n-k,n}} \right) = \frac{1}{k} \sum_{i=0}^{k-1} E_{n-i,n} - E_{n-k,n},$$

where  $E_1, E_2, \dots$  are i.i.d. random variables from standard exponential distribution. Now Renyi's representation 3.2 implies

$$\begin{aligned} & \left\{ E_{n-i,n} - E_{n-k,n} \right\}_{i=0}^{k-1} \\ & \stackrel{d}{=} \left\{ \left( \frac{E_1^*}{n} + \frac{E_2^*}{n-1} + \dots + \frac{E_{n-(i+1)}^*}{n - (n - (i+1)) + 1} + \frac{E_{n-i}^*}{n - (n - i) + 1} \right) \right. \\ & \quad \left. - \left( \frac{E_1^*}{n} + \frac{E_2^*}{n-1} + \dots + \frac{E_{n-k}^*}{n - (n - k) + 1} \right) \right\}_{i=0}^{k-1} \\ & = \left\{ \frac{E_{n-i}^*}{i+1} + \frac{E_{n-(i+1)}^*}{i+2} + \dots + \frac{E_{n-(k-2)}^*}{k-1} + \frac{E_{n-(k-1)}^*}{k} \right\}_{i=0}^{k-1} \\ & \stackrel{d}{=} \left\{ E_{k-i,k} \right\}_{i=0}^{k-1}. \end{aligned}$$

Consequently we have

$$\frac{1}{k} \sum_{i=0}^{k-1} \log \left( \frac{Y_{n-i,n}}{Y_{n-k,n}} \right) \stackrel{d}{=} \frac{1}{k} \sum_{i=0}^{k-1} E_{k-i,k} = \frac{1}{k} \sum_{i=0}^{k-1} E_i \xrightarrow{p} E[E_i] = 1$$

by the weak law of large numbers [18]. Notice that the expected value of a standard exponential is one.

□

## B Figures

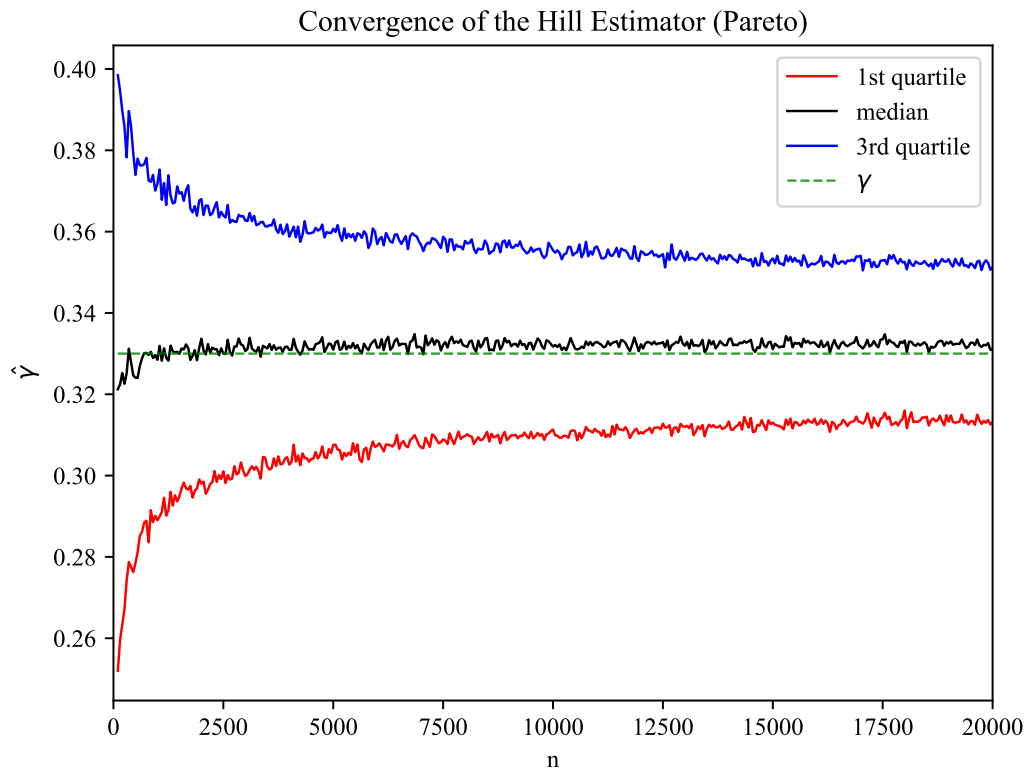


Figure B.1: Results of Monte Carlo simulation from Pareto distribution.

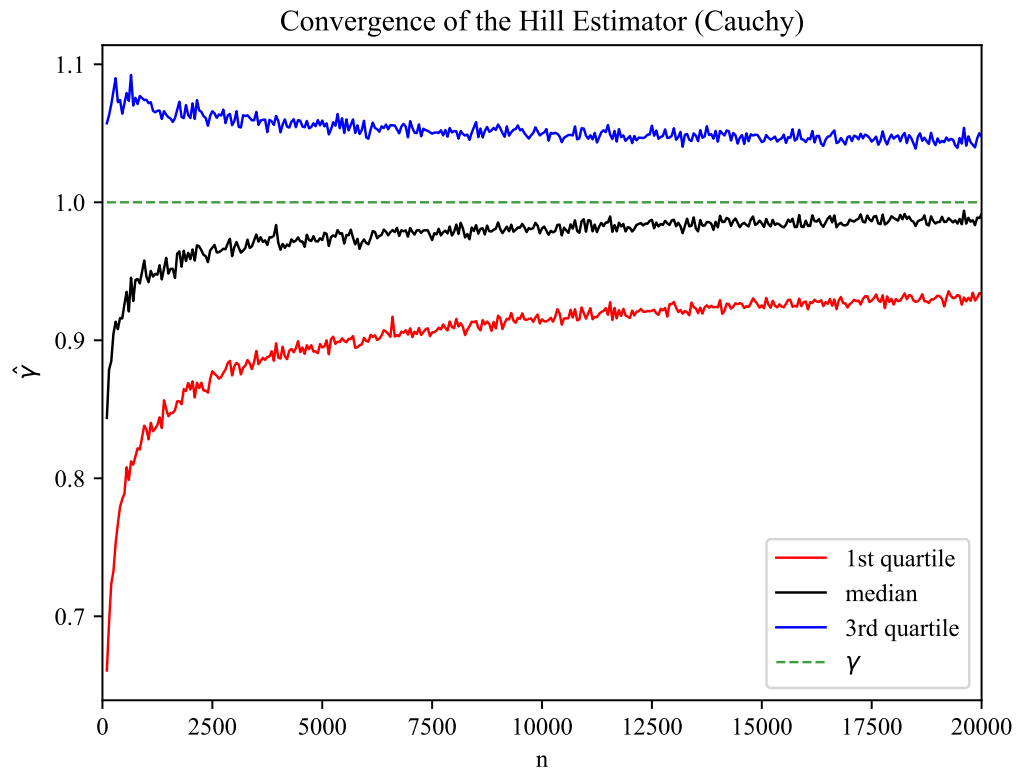


Figure B.2: Results of Monte Carlo simulation from Cauchy distribution.