

A note on Tauberian Theorems of Exponential Type

Meitner Cadena

l'université Pierre et Marie Curie-Paris 6 & CREAR, ESSEC Business
School
4 place Jussieu 75252 Paris cedex 05, France

email: meitner.cadena@etu.upmc.fr, b00454799@essec.edu,
meitner.cadena@gmail.com

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Abstract

Tauberian Theorems of exponential type provided by Kohlbecker, de Bruijn, and Kasahara are proved in only one Tauberian theorem. To this aim, the structure of those classical tauberian theorems is identified and, using a relationship recently proved by Cadena and Kratz, the relationships among its components are given.

1 Motivation and main results

Tauberian theorems of exponential type given by Kohlbecker, de Bruijn, and Kasahara appeared in 1958, 1959, and 1978, respectively. They concern equivalences between the logarithm of functions and the logarithm of their Laplace transforms when these two logarithms behave as regularly varying functions. These theorems are closely related among each other and hence their proofs may follow a same structure (see for instance §4.12 of [1]). Nevertheless these three theorems are often presented independently. For a survey on these theorems see for instance [1].

We aim to unify these theorems. This new presentation gives a general view of these classical results. As noticed by Bingham et al., a result of this

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kind was already given by de Bruijn in [3]. However, our proof is different because the structure of these tauberian theorems is revealed and the interplay among its components is shown.

Tauberian theorems of exponential type involve regularly varying (RV) functions. A measurable function $U : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ is RV with index $\alpha \in \mathbb{R}$ if, for $t > 0$, $U(xt) \sim U(x)t^\alpha$ ($x \rightarrow \infty$), where $f(x) \sim g(x)$ ($x \rightarrow x_0$) means $f(x)/g(x) \rightarrow 1$ as $x \rightarrow x_0$. The class of RV functions of index α is denoted by RV_α . If $\alpha = 0$, then U is slowly varying (SV).

With $\log(x)$ denoting the natural logarithm of x , our main result follows:

Theorem 1. *Let $a, b \in \mathbb{R}$ such that $ab(b-1) < 0$. Let $c \in \mathbb{R}$ such that $abc < 0$. Let $d = a(1-b)(-ab/c)^{b/(b-1)}$. Assume that $P(u)$ is a real function, that $\int_0^r P(u)du$ exists in the Lebesgue sense for every positive r , and that $\int_0^\infty P(u)du$ converges if $b < 0$. Put $f(s) = A + \int_0^\infty P(us)e^{cu} du$ for some real $A \in \mathbb{R}$ such that $A = 0$ if $d < 0$. Then*

$$\log(P(x)) \sim ax^b \quad x^b \rightarrow \infty \quad (1.1)$$

iff

$$\log(f(\lambda)) \sim d\lambda^{b/(1-b)} \quad (\lambda \rightarrow \infty). \quad (1.2)$$

The proof of Theorem 1 is given in the next section. A relationship provided by Cadena and Kratz [2] is used to prove this result. Part of this proof is copied from [2].

Note that in Theorem 1 we use simple forms of RV functions. They are $\phi \in \text{RV}_\alpha$ such that $\phi(x) = x^\alpha$ as $x \rightarrow \infty$. In what follows we use this kind of functions only. Hence, SV functions are assumed $L(x) = 1$ as $x \rightarrow \infty$.

As an application of our theorem we prove the Tauberian theorems given by Kohlbecker, de Bruijn, and Kasahara.

Corollary 1 (Kohlbecker's Tauberian Theorem [5], version given by Bingham et al. [1]). *Let μ be a measure on \mathbb{R} , supported by $[0; \infty)$ and finite on compact sets. Let*

$$M(\lambda) = \int_{[0; \infty)} e^{-x/\lambda} d\mu(x) \quad (\lambda > 0).$$

Let $\alpha > 1$, $B > 0$. Then

$$\log(\mu[0; x]) \sim Bx^{1/\alpha} \quad (x \rightarrow \infty)$$

iff

$$\log(M(\lambda)) \sim (\alpha - 1)(B/\alpha)^{\alpha/(\alpha-1)} \lambda^{1/(\alpha-1)} \quad (\lambda \rightarrow \infty).$$

Proof. By integration by parts $M(\lambda)$ may be rewritten as, using the change of variable $y = x/\lambda$, $M(\lambda) = \int_0^\infty e^{-y} \mu[0; y\lambda] dy$. Taking $a = B$, $b = \alpha$, and $c = -1$, gives $d = (\alpha - 1)(B/\alpha)^{\alpha/(\alpha-1)} (> 0)$, and putting $P(x) = \mu[0; x]$ and $f = M$ with $A = 0$, applying Theorem 1, the corollary then follows. \square

As mentioned above, de Bruijn's Tauberian Theorem tackled all of three Tauberian theorems of exponential type. In order to distinguish the case not concerned in the results of Kohlbecker and Kasahara, in what follows we call this case de Bruijn's Tauberian Theorem, as often found in the literature (see for instance [1], [6], and [7]).

Corollary 2 (de Bruijn's Tauberian Theorem ([3])). *Let $A > 0$. Assume that $P(u)$ is a real function and that $M(\lambda) = \lambda \int_0^\infty P(x)e^{-\lambda Ax} dx$ converges for all $\lambda > 0$. If $\beta < 0$, then for $B < 0$,*

$$\log(P(1/x)) \sim Bx^{-\beta} \quad (x \rightarrow \infty)$$

iff

$$\log(M(\lambda)) \sim B(1 - \beta) \left(\frac{\lambda}{B\beta}\right)^{\beta/(\beta-1)} \quad (\lambda \rightarrow \infty).$$

Proof. Using the changes of variables $y = \lambda x$ and $s = 1/\lambda$, $M(1/s) = \int_0^\infty e^{-y} P(sy) dy$. Taking $a = B$, $b = \beta$, and $c = -A$, gives $d = B(1 - \beta)(A/(B\beta))^{\beta/(\beta-1)} (< 0)$, and taking f as $f(1/\lambda)$ with $A = 0$, applying Theorem 1, the corollary then follows. \square

Corollary 3 (Kasahara's Tauberian Theorem [4], version given by Bingham et al. [1]). *Suppose μ is a measure on $(0; \infty)$ such that $M(\lambda) = \int_0^\infty e^{\lambda x} d\mu(x) < \infty$ for all $\lambda > 0$. Let $0 < \alpha < 1$. Then, for $B > 0$,*

$$\log \mu(x; \infty) \sim -Bx^{1/\alpha} (< 0) \quad (x \rightarrow \infty)$$

iff

$$\log(M(\lambda)) \sim (1 - \alpha)(\alpha/B)^{\alpha/(1-\alpha)} \lambda^{1/(1-\alpha)} \quad (\lambda \rightarrow \infty).$$

Proof. Noting that $\mu(0; \infty) < \infty$, by integration by parts $M(\lambda)$ may be rewritten as, using the change of variable $y = \lambda x$, $M(\lambda) = \mu(0; \infty) + \int_0^\infty e^x \mu(x/\lambda; \infty) dx$. Taking $a = -B$, $b = 1/\alpha$, and $c = 1$, gives $d = -B(1 - 1/\alpha)(B/\alpha)^{1/(\alpha-1)} = (1 - \alpha)(B/\alpha)^{\alpha/(\alpha-1)}$, and putting $P(x) = \mu(x; \infty)$ and $f = M$ with $A = \mu(0; \infty)$, applying Theorem 1, the corollary then follows. \square

2 Proof of the Main Theorem

We will use the next result proved by Cadena and Kratz [2] who introduced the class \mathcal{M} consisting of measurable functions $U : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ satisfying the property that

$$\exists \rho \in \mathbb{R}, \forall \epsilon > 0, \lim_{x \rightarrow \infty} \frac{U(x)}{x^{\rho+\epsilon}} = 0 \quad \text{and} \quad \lim_{x \rightarrow \infty} \frac{U(x)}{x^{\rho-\epsilon}} = \infty. \quad (2.3)$$

One can prove that ρ in (2.3) is unique which we denote by ρ_U .

Proposition. *Let $U : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ be a measurable function. Then, $U \in \mathcal{M}$ with $\rho_U = \eta$ iff $\log(U(x)) \sim \eta \log(x)$ ($x \rightarrow \infty$).*

Proof of the necessary condition. Let $U : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ be a measurable function.

Let $\epsilon > 0$ and $U \in \mathcal{M}$ with $\rho_U = \tau$. By definition, one has

$$\lim_{x \rightarrow \infty} \frac{U(x)}{x^{\tau+\epsilon}} = 0 \quad \text{and} \quad \lim_{x \rightarrow \infty} \frac{U(x)}{x^{\tau-\epsilon}} = \infty.$$

Hence, there exists $x_0 \geq 1$ such that, for $x \geq x_0$,

$$U(x) \leq \epsilon x^{\tau+\epsilon} \quad \text{and} \quad U(x) \geq \frac{1}{\epsilon} x^{\tau-\epsilon}.$$

Applying the logarithm function to these inequalities and dividing them by $\log(x)$ (with $x > 1$) provide

$$\frac{\log(U(x))}{\log(x)} \leq \frac{\log(\epsilon)}{\log(x)} + \tau + \epsilon \quad \text{and} \quad \frac{\log(U(x))}{\log(x)} \geq -\frac{\log(\epsilon)}{\log(x)} + \tau - \epsilon,$$

and, one then has

$$\overline{\lim}_{x \rightarrow \infty} \frac{\log(U(x))}{\log(x)} \leq \tau + \epsilon \quad \text{and} \quad \underline{\lim}_{x \rightarrow \infty} \frac{\log(U(x))}{\log(x)} \geq \tau - \epsilon,$$

from which one gets, taking ϵ arbitrary,

$$\tau \leq \underline{\lim}_{x \rightarrow \infty} \frac{\log(U(x))}{\log(x)} \leq \overline{\lim}_{x \rightarrow \infty} \frac{\log(U(x))}{\log(x)} \leq \tau,$$

and the assertion follows.

Proof of the sufficient condition. Let $\epsilon > 0$. By hypothesis, there exists $x_0 > 1$ such that, for $x \geq x_0$, $|\log(U(x))/\log(x) - \tau| \leq \epsilon/2$.

Writing, for $w \in \{\epsilon, -\epsilon\}$,

$$\frac{U(x)}{x^{\tau+w}} = \exp \left\{ \log(x) \times \left(\frac{\log(U(x))}{\log(x)} - \tau - w \right) \right\}$$

gives

$$\exp \left\{ \log(x) \times \left(-\frac{\epsilon}{2} - w \right) \right\} \leq \frac{U(x)}{x^{\tau+w}} \leq \exp \left\{ \log(x) \times \left(\frac{\epsilon}{2} - w \right) \right\},$$

and then,

$$\lim_{x \rightarrow \infty} \frac{U(x)}{x^{\tau+\epsilon}} \leq \lim_{x \rightarrow \infty} \exp \left\{ \log(x) \times \left(\frac{\epsilon}{2} - \epsilon \right) \right\} = 0$$

and

$$\lim_{x \rightarrow \infty} \frac{U(x)}{x^{\tau-\epsilon}} \geq \lim_{x \rightarrow \infty} \exp \left\{ \log(x) \times \left(\frac{\epsilon}{2} + \epsilon \right) \right\} = \infty.$$

These two limits provide $U \in \mathcal{M}$ with $\rho_U = \tau$. The proof of the proposition is complete.

Proof of Theorem 1:

Let $0 < \epsilon < |d|/2$. Note that $d > 0$ if $b > 0$, and $d < 0$ if $b < 0$.

Proof of the necessary condition. Define the function $h(x) = ax^b + cx - d$, $x > 0$. h is continuously differentiable, concave ($h''(x) = ab(b-1)x^{b-2} < 0$), and, reaches its maximum at $x_M = (-c/(ab))^{1/(b-1)} (> 0)$ and $h(x_M) = 0$, so in particular $h \leq 0$. Hence, there exists $0 < \eta < \min(x_M, 1)$ such that, for $x \in [x_M - \eta; x_M + \eta]$, $h(x) \geq -\epsilon/3$.

Let $0 < \tau < 1$ be sufficiently small, to be defined later.

Since the function P satisfies (1.1) there exists $x_0 > 0$ such that, for $x^\beta \geq x_0^\beta$,

$$\left| \frac{\log(P(x))}{ax^b} - 1 \right| \leq \tau. \tag{2.4}$$

Write, for $\xi > 1$ and $\omega \in \{\epsilon, -\epsilon\}$, using the changes of variable $v = u/\log(\xi)$ and $\psi = \log(\xi)$,

$$\frac{f((\log \xi)^{(1-b)/b})}{\xi^{d+\omega}} = Ae^{-(d+\omega)\psi} + \psi e^{-\omega\psi} \int_0^\infty P(v\psi^{1/b})e^{(cv-d)\psi} dv. \quad (2.5)$$

If $\omega = -\epsilon$ and $\psi \geq (x_0/(x_M - \eta))^b$, then, denoting $\zeta = -\operatorname{sgn}(a)\tau$ and $\theta = \operatorname{sgn}(b)\eta$, provides

$$e^{-\omega\psi} \int_0^\infty P(v\psi^{1/b})e^{(cv-d)\psi} dv \geq e^{\epsilon\psi} \int_{x_M-\eta}^{x_M+\eta} e^{(h(v)+\zeta av^b)\psi} dv \geq 2\eta e^{\frac{2}{3}\epsilon\psi} e^{\zeta a(x_M+\theta)^b\psi}.$$

Combining this and (2.5) give, choosing $\tau < \epsilon/(3a(x_M + \theta)^b)$ and noting that $\psi \rightarrow \infty$ as $\xi \rightarrow \infty$,

$$\lim_{\xi \rightarrow \infty} \frac{f((\log \xi)^{(1-b)/b})}{\xi^{d+\omega}} \geq \lim_{\psi \rightarrow \infty} \left(Ae^{-(d+\omega)\psi} + 2\eta\psi e^{\frac{2}{3}\epsilon\psi} e^{\zeta a(x_M+\theta)^b\psi} \right) = \infty.$$

Next, take $\omega = \epsilon$. Then, using the changes of variables introduced above,

$$\int_0^\infty P(v\psi^{1/b})e^{cv\psi} dv = \int_0^{x_0\psi^{-1/b}} P(v\psi^{1/b})e^{cv\psi} dv + \int_{x_0\psi^{-1/b}}^\infty P(v\psi^{1/b})e^{cv\psi} dv = I_1(\psi) + I_2(\psi)$$

On I_1 , using the change of variable $y = v\psi^{1/b}$, if $c < 0$, then by hypothesis

$$I_1(\psi) = \psi^{-1/b} \int_0^{x_0} P(y)e^{cy\psi^{1-1/b}} dy \leq \psi^{-1/b} \int_0^{x_0} P(y) dy,$$

and, if $c > 0$, then necessarily $a > 0$ and $b > 1$, and thus

$$I_1(\psi) = \psi^{-1/b} \int_0^{x_0} P(y)e^{cy\psi^{1-1/b}} dy \leq \psi^{-1/b} e^{cx_0\psi^\theta} \int_0^{x_0} P(y) dy,$$

for some $0 < \theta < 1$. Taking $\psi > (|c|x_0)^{1/(1-\theta)}$, we get

$$\lim_{\psi \rightarrow \infty} \psi e^{-(\epsilon+d)\psi} I_1(\psi) \leq \lim_{\psi \rightarrow \infty} \psi^{1-1/b} e^{-(\epsilon+d-cx_0\psi^{\theta-1})\psi} \int_0^{x_0} P(y) dy = 0.$$

On I_2 , if $b < 0$, $c < 0$ and one has

$$I_2(\psi) = \psi^{-1/b} \int_{x_0}^\infty P(y)e^{cy\psi^{-1/b}} dy = \psi^{-1/b} \int_{x_0}^\infty P(y)e^{cy\psi^{1-1/b}} dy,$$

which implies that, since $e^{cy\psi^{1-1/b}}$ is decreasing in y ,

$$\lim_{\psi \rightarrow \infty} \psi e^{-(\epsilon+d)\psi} I_2(\psi) \leq \lim_{\psi \rightarrow \infty} \psi^{1-1/b} e^{-(\epsilon+d)\psi + cx_0\psi^{1-1/b}} \int_{x_0}^{\infty} P(y) dy = 0.$$

If $b > 0$, denote ζ as above. Then, using (2.4),

$$e^{-d\psi} I_2(\psi) \leq \int_{x_0\psi^{-1/b}}^{\infty} e^{((1-\zeta)av^b + cv - d)\psi} dv.$$

Let $g(x) = (1 - \zeta)ax^b + cx - d$, $x \geq 0$, and take

$$\zeta < \operatorname{sgn}(1 - b) \left(\left[\frac{\epsilon}{2} \left(-\frac{c}{ab} \right)^{1/(1-b)} + 1 \right]^{1-b} - 1 \right).$$

Then, g is differentiable, concave ($g''(x) = (1 - \zeta)ab(b - 1)x^{b-2} < 0$), and reaches its maximum at $x_g = (-c/(ab(1 - \zeta)))^{1/(b-1)}$, and $g(x_g) = (-c/(ab))^{1/(b-1)} [(1 - \zeta)^{-1/(b-1)} - 1] (< \epsilon/2)$. Hence, $g - \epsilon/2 < 0$. This inequality and the integrability of $e^{g(x) - \epsilon/2}$ on $(0; \infty)$ allow again the application of the reverse Fatou lemma giving

$$\lim_{\psi \rightarrow \infty} \int_0^{\infty} e^{(g(v) - \epsilon/2)\psi} dv \leq \overline{\lim}_{\psi \rightarrow \infty} \int_0^{\infty} e^{(g(v) - \epsilon/2)\psi} dv \leq \int_0^{\infty} \overline{\lim}_{\psi \rightarrow \infty} e^{(g(v) - \epsilon/2)\psi} dv = 0.$$

Hence, one has

$$\lim_{\psi \rightarrow \infty} \psi e^{-(\epsilon+d)\psi} I_2(\psi) \leq \lim_{\psi \rightarrow \infty} \psi e^{-\frac{1}{2}\epsilon\psi} \int_0^{\infty} e^{(g(v) - \epsilon/2)\psi} dv = 0.$$

Combining the results on I_1 and I_2 and (2.5) give

$$\lim_{\xi \rightarrow \infty} \frac{f((\log \xi)^{(1-b)/b})}{\xi^{d-\omega}} = \lim_{\psi \rightarrow \infty} (Ae^{-(d+\omega)\psi} + \psi e^{-(\omega+d)\psi} I_1(\psi) + \psi e^{-(\omega+d)\psi} I_2(\psi)) \leq 0.$$

Therefore, f being positive and measurable, $U(\xi) = f((\log \xi)^{(1-b)/b}) \in \mathcal{M}$ with $\rho_U = d$, and then, applying the Proposition,

$$\lim_{\xi \rightarrow \infty} \frac{\log(f((\log \xi)^{(1-b)/b}))}{\log(\xi)} = d.$$

By using the change of variable $\lambda = (\log \xi)^{(1-b)/b}$ the assertion follows.

Proof of the sufficient condition. Let $\epsilon > 0$. Suppose that the function

f satisfies (1.2). Rewriting this limit as, using the change of variable $\xi = \exp \{ \lambda^{b/(1-b)} \}$,

$$\lim_{\xi \rightarrow \infty} \frac{\log (f((\log \xi)^{(1-b)/b}))}{\log(\xi)} = d,$$

this means that, applying the Proposition, $U \in \mathcal{M}$ with $\rho_U = d$ where U is defined as above. So, one has

$$\lim_{\xi \rightarrow \infty} \frac{f((\log \xi)^{(1-b)/b})}{\xi^{d+\epsilon}} = 0 \quad \text{and} \quad \lim_{\xi \rightarrow \infty} \frac{f((\log \xi)^{(1-b)/b})}{\xi^{d-\epsilon}} = \infty,$$

i.e., using the changes of variable $v = u / \log(\xi)$ and $\psi = \log(\xi)$ and denoting $Q(x) = \log(P(x))$,

$$\lim_{\psi \rightarrow \infty} \psi \int_0^\infty e^{(Q(v\psi^{1/b})/\psi + cv - d - \epsilon)\psi} dv = 0 \quad \text{and} \quad \lim_{\psi \rightarrow \infty} \psi \int_0^\infty e^{(Q(v\psi^{1/b})/\psi + cv - d + \epsilon)\psi} dv = \infty. \quad (2.6)$$

We claim that, given $\psi > 0$,

$$Q(v\psi^{1/b})/\psi + cv - d \leq 0 \text{ almost surely (a.s.) for all } v > 0. \quad (2.7)$$

Assuming there exist $\nu > 0$ and $v_1 > 0$ such that $Q(v_1\psi^{1/b})/\psi + cv_1 - d \geq 2\nu$ a.s., this means that there exists $\eta > 0$ such that, for $v \in [v_1 - \eta; v_1 + \eta]$, $Q(v\psi^{1/b})/\psi + cv - d \geq \nu$. Hence, taking $\epsilon = \nu/2$, one gets

$$\lim_{\psi \rightarrow \infty} \psi \int_0^\infty e^{(Q(v\psi^{1/b})/\psi + cv - d - \epsilon)\psi} dv \geq \lim_{\psi \rightarrow \infty} \psi \int_{v_1 - \eta}^{v_1 + \eta} e^{\nu\psi/4} dv = \lim_{\psi \rightarrow \infty} 2\eta\psi e^{\nu\psi/4} = \infty,$$

which contradicts the first limit in (2.6).

Furthermore, we claim that, given $\psi > 0$,

$$\text{there exists } v_0 > 0 \text{ such that } Q(v_0\psi^{1/b})/\psi + cv_0 - d = 0. \quad (2.8)$$

Assuming for all $v > 0$ that $Q(v\psi^{1/b})/\psi + cv - d < 0$, since (2.7) is satisfied, then, using the change of variable $z = v\psi^{1/b}$, gives

$$Q(z) < \frac{d - cv}{v^b} z^b.$$

Now, taking the following limits on v provides, for any $z > 0$,

$$Q(z) \leq \begin{cases} \lim_{v \rightarrow 0^+} \frac{d - cv}{v^b} z^b = 0 & \text{if } b < 0 \\ \lim_{v \rightarrow 0^+} \frac{d - cv}{v^b} z^b = -\infty & \text{if } 0 < b < 1 \text{ because } c > 0 \\ \lim_{v \rightarrow \infty} \frac{d - cv}{v^b} z^b = 0 & \text{if } b > 1. \end{cases}$$

This implies that $P \equiv 0$ if $0 < b < 1$ and $P \equiv 1$ if $b < 0$ or $b > 0$, which contradicts the hypothesis (1.1).

Introducing the change of variable $z = v_0 \psi^{1/b}$ in the relationship given in (2.8) gives, for $z > 0$,

$$Q(z) = \frac{d - cv_0}{v_0^b} z^b.$$

This implies that Q is continuously differentiable, concave, and then that $Q(v\psi^{1/b})/\psi + cv - d$ has a unique maximum at v ; i.e. v_0 . This maximum satisfies

$$\psi^{1/b} \frac{Q'(v_0 \psi^{1/b})}{\psi} + c = \psi^{1/b-1} \frac{d - cv_0}{v_0^b} b (v_0 \psi^{1/b})^{b-1} + c = 0,$$

which implies $b(d - cv_0) = -cv_0$, i.e. $v_0 = db/(c(b - 1))$. v_0 is positive and satisfies $v_0 = x_M$. Straightforward computations give $a = (d - cv_0)/v_0^b$. So Q can be rewritten as $Q(z) = az^b$. Hence (1.1) follows.

3 Discussion of results

Our proof of the Tauberian theorems given by Kohlbecker, de Bruijn, and Kasahara dissects the functioning of these theorems. A function like $h(x) = ax^b + cx - d$, $x > 0$, is identified, which has two key properties in order to establish these theorems: concavity and non-positivity. The first of these properties gives the possible Tauberian theorems: $ab(b - 1) < 0$, from which exactly three solutions are possible, each one corresponding to a known Tauberian theorem of exponential type. The second property guarantees the convergence of integrals of type $\int_0^\infty P(us)e^{cu} du$ and lets the control of this integral at $v_0 > 0$. This point satisfies $h(v_0) = 0$, the unique maximum

of h . Note that if $h(v_0) > 0$ or $h(v_0) < 0$ one cannot obtain those Tauberian theorems. From the relationship $h'(v_0) = 0$ the condition for c is derived, and from $h(v_0) = 0$ the corresponding condition for d . Finally, the Proposition allows the identification of the disposition of the logarithms of functions.

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