# ON AFFINITY RELATING TWO POSITIVE MEASURES AND THE CONNECTION COEFFICIENTS BETWEEN POLYNOMIALS ORTHOGONALIZED BY THESE MEASURES 

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#### Abstract

We consider two positive, normalized measures $d A(x)$ and $d B(x)$ related by the relationship $d A(x)=\frac{C}{x+D} d B(x)$ or by $d A(x)=\frac{C}{x^{2}+E} d B(x)$ and $d B(x)$ is symmetric. We show that then the polynomial sequences $\left\{a_{n}(x)\right\}$, $\left\{b_{n}(x)\right\}$ orthogonal with respect to these measures are related by the relationship $a_{n}(x)=b_{n}(x)+\kappa_{n} b_{n-1}(x)$ or by $a_{n}(x)=b_{n}(x)+\lambda_{n} b_{n-2}(x)$ for some sequences $\left\{\kappa_{n}\right\}$ and $\left\{\lambda_{n}\right\}$. We present several examples illustrating this fact and also present some attempts for extensions and generalizations. We also give some universal identities involving polynomials $\left\{b_{n}(x)\right\}$ and the sequence $\left\{\kappa_{n}\right\}$ that have a form of Fourier series expansion of the Radon-Nikodym derivative of one measure with respect to the other.


## 1. Introduction

We study relationship between the pair of orthogonal polynomials and the pair of measures that make these polynomials orthogonal. This problem has practical importance. If solved in full generality would enable quick and easy way of finding sets of orthogonal polynomials for a given measure simplifying the usual path of the Gram-Smith orthogonalization. Besides it would provide quick and easy way of finding 'connection coefficients' between the two analyzed sets of orthogonal polynomials. On its side 'connection coefficients', as it is well known supply many useful informations about the properties of the involved sets of polynomials. So far in the literature devoted to connection coefficients like [15, [5], [2] the authors studied the properties of these coefficients and their relationship to zeros of orthogonal polynomials in question without referring to the properties of orthogonalizing measures.

We are solving the problem of affinity between connection coefficients and measures that make polynomials orthogonal only partially. There are still many challenging questions that we pose in Section 4 and which are unsolved to our knowledge.

To be more precise we will assume throughout the paper the following setting:

[^0]We consider two sequences of monic, orthogonal polynomials $\left\{a_{n}\right\}$ and $\left\{b_{n}\right\}$ such that their 3 -term recurrences are as given below:

$$
\begin{align*}
& a_{n+1}(x)=\left(x-\alpha_{n}\right) a_{n}(x)-\hat{\alpha}_{n-1} a_{n-1}(x)  \tag{1.1}\\
& b_{n+1}(x)=\left(x-\beta_{n}\right) b_{n}(x)-\hat{\beta}_{n-1} b_{n-1}(x) \tag{1.2}
\end{align*}
$$

with $a_{-1}(x)=b_{-1}(x)=0, a_{0}(x)=b_{0}(x)=1$.
In [14, Proposition 1 it was shown that if these measures are such that $\operatorname{supp} A=$ $\operatorname{supp} B$ and $d A(x)=\frac{1}{P_{r}(x)} d B(x)$, where $P_{r}$ is a polynomial of order $r$, then there exist $r$ sequences $\left\{c_{n}^{(j)}\right\}_{n \geq 1,1 \leq j \leq r}$ such that

$$
\begin{equation*}
a_{n}(x)=b_{n}(x)+\sum_{j=1}^{r} c_{n}^{(j)} b_{n-j}(x) \tag{1.3}
\end{equation*}
$$

In the cited result it was not presented how to relate 3 -term recurrence satisfied by say the set $\left\{b_{n}\right\}$ and the form of the polynomial $P_{r}$ to the form of the coefficients $\left\{c_{n}^{(j)}\right\}_{n \geq 1,1 \leq j \leq r}$.

Remark 1. Notice that our assumptions mean in fact that $d A \ll d B$ and $\frac{d A(x)}{d B(s)}$ $=\frac{1}{P_{r}(x)}$, where $\frac{d A(x)}{d B(s)}$ denotes Radon-Nikodym derivative of $d A$ with respect to $d B$.

Relationship like (1.3) between sets of orthogonal polynomials is called quasiorthogonality as defined in [3] and [4]. More precisely polynomials $\left\{a_{n}\right\}$ that are related to polynomials $\left\{b_{n}\right\}$ by (1.3) are called quasi-orthogonal provided $b_{n}^{\prime} s$ are orthogonal. Thus our problem can be expressed in the following way: If the measures $d A$ and $d B$ are related by $d A(x)=\frac{1}{P_{r}(x)} d B(x)$, then there exists $r$ sequences of numbers $\left\{c_{n}^{(j)}\right\}_{n \geq 1,1 \leq j \leq r}$ such that quasi-orthogonal polynomials defined by (1.3) are orthogonal (with respect to $d A$ ).

There exits also another, similar in a way, path of research followed by Pascal Maroni and his associates. The results of their research were presented in the series of papers [8]-[13]. The problem considered by Maroni concerns general linear regular (i.e. possessing sets of orthogonal polynomials) functionals $u$ and $v$ (not necessarily in the form of measure) defined on the linear space of polynomials and related to one another by the relationship

$$
x^{m} u=\lambda v
$$

where $m$ is a fixed integer (in Maroni's papers $m \leq 4$ ) and $\lambda$ a fixed complex number. In majority of cases he assumes that regular $v$ has a form $<v, p>$ $=\int V(x) p(x) d x$ where $p$ is a polynomial while $V$ is a locally integrable function rapidly decaying at infinity. Maroni is interested in conditions for the existence of regular $u$ and also in the relationship between the sets of polynomials orthogonal with respect to $v$ and $u$. In his studies he showed that orthogonal polynomials of $u$ must be linear combinations of the last $m+1$ (i.e. are quasi-orthogonal). He also obtained some (mostly in the case of $m=1$ ) recursive relations relating sets of orthogonal polynomials of $u$ and $v$ and coefficients of the quasi-orthogonality.

Notice that even if $v$ is a measure $u$ may be not. Moreover it is expressed (as it follows from Maroni's papers) by derivatives of Dirac's delta and Cauchy's principal
value. The existence conditions are not simple and constitute major part of these papers.

That is why although some of the results obtained below were first discovered by Maroni we will repeat them for the sake of uniformity of treatment. Of course we will point out which of them were mentioned in Maroni's papers.

In the present paper we continue the research started in [14] and relate the 3term recurrence coefficients satisfied by $\left\{b_{n}\right\}$ and the exact form of the polynomial $P_{r}$ for $r=1,2$ to coefficients $c_{n}^{(1)}$ for $r=1$ and $c_{n}^{(1)}, c_{n}^{(2)}$ for $r=2$. We also give the 3 -term recurrence coefficients of the polynomials $\left\{a_{n}\right\}$. Besides we also provide certain universal identities satisfied by the polynomials $\left\{b_{n}\right\}$, coefficients $\left\{\hat{\beta}_{n}\right\}$, $\left\{c_{n}^{(1)}\right\}$ and the parameters of the polynomials $P_{r}$.

The paper is organized as follows: In the next Section 2 we present our main result concerning the case $r=1$ and illustrate it by 3 examples concerning well known families of polynomials like Jacobi or Charlier. Examples are presented in Section 3. Less complete or less simple and nice results are presented in Section 4 Here also we will illustrate the developed ideas by a few examples. Finally Section 5 contains less interesting or lengthy proofs of our results.

## 2. Main Results

The simplest but also the most important case is when $r=1$. This case is treated by the theorem below:

Theorem 1. Let the sequence of monic, orthogonal polynomials $\left\{b_{n}\right\}$ be defined by the 3-term recurrence (1.2). Suppose that $d B(x)$ is the positive measure that makes these polynomials orthogonal. Let us consider another normalized measure $d A(x)$ related to $d B(x)$ by the relationship:

$$
\begin{equation*}
d A(x)=\frac{C}{x+D} d B(x) \tag{2.1}
\end{equation*}
$$

so that $\frac{C}{(x+D)} \geq 0$ on the support of $d B$ (and of $d A$ ).
Then there exists a number sequence $\left\{\kappa_{n}\right\}$ defined by the relationship:

$$
\begin{equation*}
\kappa_{n}=\beta_{n-1}-\frac{\hat{\beta}_{n-2}}{\kappa_{n-1}}+D, \tag{2.2}
\end{equation*}
$$

$n \geq 2$ with $\kappa_{1}=\beta_{0}+D-C$, such that the sequence of monic polynomials defined by:

$$
\begin{equation*}
a_{n}(x)=b_{n}(x)+\kappa_{n} b_{n-1}(x) . \tag{2.3}
\end{equation*}
$$

satisfies the 3-term recurrence (1.1) with:

$$
\begin{align*}
\alpha_{n} & =\beta_{n}+\kappa_{n}-\kappa_{n+1},  \tag{2.4}\\
\hat{\alpha}_{n-1} & =\kappa_{n} \frac{\hat{\beta}_{n-2}}{\kappa_{n-1}} \tag{2.5}
\end{align*}
$$

and is orthogonal with respect to the measure $d A(x)$.
Remark 2. Recursive equations (2.2) and (2.4) were obtained by P. Maroni in 8 as sidelines of his results obtained in a slightly different context. (2.5) was obtained in a different but equivalent form.

Proof. Is shifted to section 5
We have immediate remarks, observations and corollaries
Remark 3. All coefficients $\kappa_{n}$ have the same sign i.e. are either all positive or all negative. This follows the fact that since $d A(x)$ and $d B(x)$ are positive measures we must have nonnegative both $\hat{\alpha}_{n}$ and $\hat{\beta}_{n}$. Then we use (2.5).
Remark 4. Notice that following relationship $\kappa_{1}=\beta_{0}+D-C$ and (2.3), $\frac{C}{x+D}$ can be written as $\frac{1}{a_{1}(x) / C+1}$ which fits assumptions of Proposition 1 of [14].
Remark 5. Following (2.5) and the fact that $\hat{\alpha}_{n-1} \geq 0$ we deduce that either $\beta_{n}$ $+D \geq 0$ or $\beta_{n}+D \leq 0$ for all $n \geq 1$. Consequently either we have for all $n \geq 0$

$$
\beta_{n-1}+D \leq \kappa_{n} \leq 0 \text { or } 0 \leq \kappa_{n} \leq \beta_{n-1}+D
$$

Corollary 1. Under assumptions of Theorem 1 we have

$$
\begin{equation*}
b_{n}(x)=a_{n}(x)+\sum_{j=1}^{n}(-1)^{j}\left(\prod_{k=n-j+1}^{n} \kappa_{k}\right) a_{n-j}(x) \tag{2.6}
\end{equation*}
$$

for $n=0,1,2, \ldots$ Further under additional assumption that $\int_{\operatorname{supp} B} \frac{1}{(x+D)^{2}} d B(x)<$ $\infty$ we have:

$$
1+\sum_{n \geq 1}\left(\prod_{k=1}^{n} \frac{\kappa_{k}}{\hat{\beta}_{k-1}}\right)^{2}=C^{2} \int_{\operatorname{supp} B} \frac{1}{(x+D)^{2}} d B(x)
$$

and

$$
\begin{equation*}
\frac{C}{x+D}=1+\sum_{n \geq 1}(-1)^{n}\left(\prod_{k=1}^{n} \frac{\kappa_{k}}{\hat{\beta}_{k-1}}\right) b_{n}(x) \tag{2.7}
\end{equation*}
$$

on $\operatorname{supp} B$ in $L_{2}(\operatorname{supp} B, \mathcal{B}, d B(x))$. If additionally $\sum_{n \geq 1}\left(\prod_{k=1}^{n} \frac{\kappa_{k}}{\widehat{\beta}_{k-1}}\right)^{2} \log ^{2} n<$ $\infty$, then convergence in (2.7) is almost $(d B(x))$ pointwise on $\operatorname{supp} B$.
Proof. Using (2.6) we have $b_{n}(x)+\kappa_{n} b_{n-1}(x)=a_{n}+\sum_{j=1}^{n}(-1)^{j}\left(\prod_{k=n-j+1}^{n} \kappa_{k}\right) a_{n-j}(x)$ $+\kappa_{n} a_{n-1}+\sum_{j=1}^{n-1}(-1)^{j}\left(\prod_{k=n-j}^{n} \kappa_{k}\right) a_{n-1-j}(x)=a_{n}$. Now we apply idea of ratio of density expansion presented in 14 and use (2.6). On the way we notice that the requirement that both measures (i.e. $d A$ and $d B$ ) have densities with respect to Lebesgue measure can be dropped. We also utilize the fact that $\int_{\operatorname{supp} B} b_{n}^{2}(x) d B(x)$ $=\prod_{k=0}^{n-1} \hat{\beta}_{k}$ which follows Favard's Theorem. The we also use Rademacher- - Menshov theorem concerning almost sure convergence of $L_{2}$ converging Fourier series.

## 3. Examples

To illustrate how simple and easy is to utilize the presented in the previous section observations and rules let us consider the following few examples:

It should be remarked that although examples concerning Jacobi and Legendre polynomials were considered by Maroni in [8] they were illustrating different phenomena discovered by Maroni in this paper. In particular formulae (3.4), (3.5) and (3.6) do not appear in Maroni's paper. We present them in order to illustrate the use of equations (2.2), (2.4), (2.5) and expansion (2.7).

Example 1 (Jacobi polynomials). Recall (e.g. basing on [1 or [6) that monic Jacobi polynomials $J_{n}^{(\alpha, \beta)}(x)$ satisfy the following 3-term recurrence:

$$
\begin{align*}
& J_{n+1}^{(\alpha, \gamma)}(z)=\left(x+\frac{\alpha^{2}-\gamma^{2}}{(2 n+\alpha+\gamma+2)(\alpha+\gamma+2 n)}\right) J_{n}^{(\alpha, \gamma)}(x)  \tag{3.1a}\\
& \quad-\frac{4 n(\alpha+\gamma+n)(n+\alpha)(n+\gamma)}{(\alpha+\gamma+2 n-1)(2 n+\alpha+\gamma)^{2}(\alpha+\gamma+2 n+1)} J_{n-1}^{(\alpha, \gamma)}(z) \tag{3.1b}
\end{align*}
$$

Besides one knows also that the normalized measure that makes these polynomials orthogonal is the following:

$$
f(x ; \alpha, \gamma)=\frac{\Gamma(\alpha+\gamma+2)}{2^{\alpha+\gamma+1} \Gamma(\gamma+1) \Gamma(\alpha+1)}(1-x)^{\alpha}(1+x)^{\gamma},
$$

where $\Gamma(\eta)$ denotes value of the Gamma function at $\eta$, for $|x|<1$ and $\alpha, \gamma>-1$.
Now let us take $\alpha>0, \gamma>-1, d B(x)=f(x ; \alpha, \gamma) d x$ and $d A(x)=f(\alpha-1, \gamma) d x$, $b_{n}(x)=J_{n}^{(\alpha, \gamma)}(x)$ and $a_{n}(x)=J_{n}^{(\alpha-1, \gamma)}(x)$. One can easily notice that $d A(x)=$ $\frac{C}{(-1+x)} d B(x)$, where $C=-\frac{2 \alpha}{\alpha+\gamma+1}$, hence $D=-1$. From (3.1) it follows also that

$$
\begin{align*}
\beta_{n} & =-\frac{\alpha^{2}-\gamma^{2}}{(2 n+\alpha+\gamma+2)(\alpha+\gamma+2 n)},  \tag{3.2}\\
\hat{\beta}_{n-1} & =\frac{4 n(\alpha+\gamma+n)(n+\alpha)(n+\gamma)}{(\alpha+\gamma+2 n-1)(2 n+\alpha+\gamma)^{2}(\alpha+\gamma+2 n+1)} . \tag{3.3}
\end{align*}
$$

Thus $\kappa_{1}=\beta_{0}+D-C=-\frac{\alpha^{2}-\gamma^{2}}{(\alpha+\gamma+2)(\alpha+\gamma)}+\frac{2 \alpha}{\alpha+\gamma+1}-1=-2 \frac{\gamma+1}{(\alpha+\gamma+1)(\alpha+\gamma+2)}$ and consequently coefficients $\kappa_{n}$ satisfy recursive equation:

$$
\kappa_{n}=\beta_{n-1}-1-\frac{\hat{\beta}_{n-2}}{\kappa_{n-1}}
$$

for $n \geq 2$. One can also easily notice that

$$
\begin{equation*}
\kappa_{n}=-\frac{2 n(n+\gamma)}{(\alpha+\gamma+2 n)(\alpha+\gamma+2 n-1)} \tag{3.4}
\end{equation*}
$$

satisfies above mentioned recursive equation. Hence

$$
\begin{equation*}
J_{n}^{(\alpha-1, \gamma)}(x)=J_{n}^{(\alpha, \gamma)}(x)+\kappa_{n} J_{n-1}^{(\alpha, \gamma)}(x) \tag{3.5}
\end{equation*}
$$

As far as application of Corollary 1 is concerned we have the following identity true for $\alpha>1, \gamma>-1$, and almost all $|x|<1$ :

$$
\begin{equation*}
1=\frac{\alpha+\gamma+1}{2 \alpha}(1-x)\left(1+\sum_{n \geq 1}^{\infty} \frac{(\alpha+\gamma+1)_{2 n}}{2^{n}(\alpha+\gamma+1)(\alpha+1)_{n}(\alpha+\gamma+1)_{n}} J_{n}^{(\alpha, \gamma)}(x)\right), \tag{3.6}
\end{equation*}
$$

where we use the so called Pochhammer symbol $(a)_{n}=a(a+1) \ldots(a+n-1)$. This is so since $\frac{\kappa_{n}}{\gamma_{n-1}}=-\frac{(\alpha+\gamma+2 n+1)(\alpha+\gamma+2 n)}{2(\alpha+n)(\alpha+\gamma+n)}$, by (3.3) and (3.4) and because $\int_{-1}^{1} \frac{1}{(1-x)^{2}} d B(x)<\infty$ for $\gamma>-1, \alpha-2>-1$.

Example 2 (Charlier polynomials). Basing on [7] let us recall that monic Charlier polynomials $\left\{c_{n}(x ; \lambda)\right\}_{n \geq-1}$ are polynomials given by the following 3-term recurrence

$$
c_{n+1}(x ; \lambda)=(x-n-\lambda) c_{n}(x ; \lambda)-n \lambda c_{n-1}(x ; \lambda)
$$

with $c_{-1}(x ; \lambda)=0, c_{0}(x ; \lambda)=1$. For $\lambda>0$ they are orthogonal with respect to discrete measure concentrated at nonnegative integers with mass at $n$ equal to $\exp (-\lambda) \frac{\lambda^{n}}{n!}, n \geq 0$. Another words this measure is the Poisson normalized measure.

In order not to complicate too much let us take $d B(n)=\exp (-\lambda) \frac{\lambda^{n}}{n!}$ and $d A(n)$ $=\frac{C}{n+1} d B(n)$ for $n=0,1, \ldots$. Since $\sum_{n \geq 0}^{\infty} \frac{\lambda^{n}}{(n+1)!}=\frac{(\exp (\lambda)-1)}{\lambda}$ we see that $C=$ $\frac{\lambda \exp (\lambda)}{\exp (\lambda)-1}$. Naturally we have also $D=1$ and $\beta_{n}=n+\lambda$ and $\hat{\beta}_{n-1}=n \lambda$, hence $\kappa_{1}$ $=\lambda+1-\frac{\lambda \exp (\lambda)}{-1+\exp (\lambda)}=\frac{\exp (\lambda)-1-\lambda}{\exp (\lambda)-1}$. Thus recursive equation satisfied by coefficients $\kappa_{n}$ is the following:

$$
\kappa_{n}=n+\lambda-\frac{(n-1) \lambda}{\kappa_{n-1}}
$$

$n \geq 2$. In particular we have $\kappa_{2}=2 \frac{\exp (\lambda)-1-\lambda-\lambda^{2} / 2}{\exp (\lambda)-1-\lambda}, \kappa_{3}=3 \frac{\exp (\lambda)-1-\lambda-\lambda^{2} / 2-\lambda^{3} / 3 \text { ! }}{\exp (\lambda)-1-\lambda-\lambda^{2} / 2}$ and in general it is easy to see that

$$
\kappa_{n}=n \frac{\exp (\lambda)-\sum_{j=0}^{n} \frac{\lambda^{j}}{j!}}{\exp (\lambda)-\sum_{j=0}^{n-1} \frac{\lambda^{j}}{j!}}=n \frac{\sum_{j \geq n+1} \frac{\lambda^{j}}{j!}}{\sum_{j \geq n} \frac{\lambda^{j}}{j!}} .
$$

Thus we have in particular

$$
\begin{aligned}
a_{n}(x) & =c_{n}(x)+\kappa_{n} c_{n-1}(x) \\
\alpha_{n} & =n+\lambda+\kappa_{n}-\kappa_{n+1} \\
\hat{\alpha}_{n-1} & =\frac{\lambda n\left(\sum_{j \geq n+1} \frac{\lambda^{j}}{j!}\right)\left(\sum_{j \geq n-1} \frac{\lambda^{j}}{j!}\right)}{\left(\sum_{j \geq n} \lambda^{j}\right)^{2}}
\end{aligned}
$$

As the application of Corollary 1 we have the following identity true for $\lambda>0$ and $x=0,1, \ldots$

$$
\begin{equation*}
e^{\lambda}=(1+x)\left(\frac{e^{\lambda}-1}{\lambda}+\sum_{n \geq 1}(-1)^{n} c_{n}(x ; \lambda) \sum_{k \geq n+1} \frac{\lambda^{k-n-1}}{k!}\right) \tag{3.7}
\end{equation*}
$$

This is so since $\frac{\kappa_{n}}{\hat{\beta}_{n-1}}=\frac{\exp (\lambda)-\sum_{j=0}^{n} \frac{\lambda_{j}^{j}}{j!}}{\lambda\left(\exp (\lambda)-\sum_{j=0}^{n-1} \frac{\lambda j}{j!}\right)}$ and consequently $\prod_{k=1}^{n} \frac{\kappa_{k}}{\widehat{\beta}_{k-1}}=\frac{\exp (\lambda)-\sum_{k=0}^{n} \frac{\lambda^{k}}{k!}}{\lambda^{n}}$ $=\sum_{k \geq n+1} \frac{\lambda^{k-n}}{k!}$. Let us observe that (3.7) is not satisfied for non-positive integer $x$.

Example 3 (Legendre polynomials). As it is known Legendre polynomials are the Jacobi polynomials with $\alpha, \gamma=0$. As $d B(x)$ let us consider measure with the density $f(x ; 0,0)=1 / 2$ on $[-1,1]$. As dA $(x)$ let us consider measure with the density $\frac{C}{2(3-x)}$ on $[-1,1]$. Parameter $C$ we get by direct integration, namely $C=\frac{-2}{\ln 2}$ while $D=$ -3 . Further using (3.2) and (3.3) we get:

$$
\beta_{n}=0, \hat{\beta}_{n-1}=\frac{n^{2}}{(2 n-1)(2 n+1)}
$$

Hence $\kappa_{1}=0-3+\frac{2}{\ln 2}$ and consequently coefficients $\kappa_{n}$ are given by the following recursive equation:

$$
\kappa_{n+1}=-3-\frac{n^{2}}{(2 n-1)(2 n+1) \kappa_{n}}
$$

for $n \geq 1$. In particular we get $\kappa_{2}=-3-\frac{1}{3(-3+2 / \ln 2)}=-\frac{(26 \ln 2-18)}{9 \ln 2-6}$. Finally we deduce that polynomials defined by

$$
a_{n}(x)=J_{n}^{(0,0)}+\kappa_{n} J_{n-1}^{(0,0)}(x),
$$

are orthogonal with respect to the measure with the density: $\frac{2}{(3-x) \ln 2}$ on $[-1,1]$.

## 4. Extensions and open problems

In this section we are going to present some generalizations of the results of Section 2. The results are not as nice and compact as the ones presented above that is why we present them here. We will also pose some open problems that appeared immediately when writing the article.

Let us return to the setting that was presented in the Introduction and consider the case $r=2$. Let us assume that measures $d A$ and $d B$ are related to one another by the relationship

$$
\begin{equation*}
d A(x)=\frac{C}{x^{2}+D x+E} d B(x) \tag{4.1}
\end{equation*}
$$

and that constants $C, D, E$ are such that $\frac{C}{x^{2}+C x+E} \geq 0$ on supp $B$ and that measure $d A$ is normalized. Following cited already [14], Proposition 1 we deduce that then polynomials $\left\{a_{n}\right\}$ and $\left\{b_{n}\right\}$ orthogonal with respect to these measures are related by the relationship

$$
\begin{equation*}
a_{n}(x)=b_{n}(x)+\kappa_{n} b_{n-1}(x)+\lambda_{n} b_{n-2}(x), \tag{4.2}
\end{equation*}
$$

for some number sequences $\left\{\kappa_{n}\right\}$ and $\left\{\lambda_{n}\right\}$. given in the Proposition below:
Proposition 1. Suppose normalized, positive measures $d A$ and $d B$ are related to one another by 4.1). Let further polynomial sequences $\left\{a_{n}\right\}$ and $\left\{b_{n}\right\}$ orthogonal with respect to these measures satisfy respectively 3-term recurrence (1.1) and (1.2). Then there exist two number sequences $\left\{\kappa_{n}\right\}$ and $\left\{\lambda_{n}\right\}$ such that (4.2) is satisfied. Moreover number sequences $\left\{\kappa_{n}\right\},\left\{\lambda_{n}\right\},\left\{\alpha_{n}\right\}\left\{\hat{\alpha}_{n}\right\},\left\{\beta_{n}\right\},\left\{\hat{\beta}_{n}\right\}$ are related to one another by the system of equations:

$$
\begin{align*}
\kappa_{n+1}+\alpha_{n} & =\beta_{n}+\kappa_{n},  \tag{4.3}\\
\lambda_{n+1}+\alpha_{n} \kappa_{n}+\hat{\alpha}_{n-1} & =\hat{\beta}_{n-1}+\kappa_{n} \beta_{n-1}+\lambda_{n},  \tag{4.4}\\
\alpha_{n} \lambda_{n}+\hat{\alpha}_{n-1} \kappa_{n-1} & =\kappa_{n} \hat{\beta}_{n-2}+\lambda_{n} \beta_{n-2},  \tag{4.5}\\
\hat{\alpha}_{n-1} \lambda_{n-1} & =\lambda_{n} \hat{\beta}_{n-3} . \tag{4.6}
\end{align*}
$$

with $\lambda_{1}=0$ and $\kappa_{1}, \kappa_{2}$ and $\lambda_{2}$ defined as solutions of the system of 7 equations $0=\int_{\operatorname{supp} B}\left(b_{1}(x)+\kappa_{1}\right) d A(x)=\int_{\operatorname{supp} B}\left(b_{2}(x)+\kappa_{2} b_{1}(x)+\lambda_{2}\right) d A(x)=$
$\int_{\text {supp } B}\left(b_{2}(x)+\kappa_{2} b_{1}(x)+\lambda_{2}\right)\left(b_{1}(x)+\kappa_{1}\right) d A(x)=\int_{\text {supp } B} b_{1}(x)\left(x^{2}+D x+E\right) d A(x)$
$=\int_{\operatorname{supp} B} b_{2}(x)\left(x^{2}+D x+E\right) d A(x), \int_{\operatorname{supp} B}\left(x^{2}+D x+E\right) d A(x)=C$,
$\int_{\operatorname{supp} B} b_{1}^{2}(x)\left(x^{2}+D x+E\right) d A(x)=\hat{\beta}_{0}$ with 4 additional unknowns
$\int_{\text {supp } B} b_{1}(x) d A(x), \int_{\operatorname{supp} B} b_{2}(x) d A(x), \int_{\operatorname{supp} B} b_{1}(x) b_{2}(x) d A(x), \int_{\operatorname{supp} B} b_{2}^{2}(x) d A(x)$.
Proof. Uninteresting proof is shifted to Section 5 ,
Visibly it is hard to solve system of equations (4.3)-(4.6) for $\left\{\kappa_{n}, \lambda_{n}, \alpha_{n}, \hat{\alpha}_{n}\right\}$ in general. Below we will present one example where it is simple.

Example 4 (Kesten-McKay distribution). This example concerns measure that is called Kesten-McKay. It appeared in probability in the context of random matrices. One of the particular examples of its density is the density of the form:

$$
f(x ; y, \rho)=\frac{\left(1-\rho^{2}\right) \sqrt{4-x^{2}}}{2 \pi\left(\left(1-\rho^{2}\right)^{2}-\rho\left(1+\rho^{2}\right) x y+\rho^{2}\left(x^{2}+y^{2}\right)\right)}
$$

for $|x|,|y| \leq 2, \rho^{2}<1$. To see that $\int_{-2}^{2} f(x ; y, \rho) d x=1$ for all $|y| \leq 2$ and $\rho^{2}<1$ is difficult hence to obtain sequence of polynomials orthogonal with respect to it by Gram-Schmidt procedure is quite hard. As one can easily see this density is a particular example of the relationship (4.1) with $d B(x)=\frac{1}{2 \pi} \sqrt{4-x^{2}} d x, b_{n}(x)=$ $U_{n}(x / 2)$, where $U_{n}(x)$ are the Chebyshev polynomials of the second kind (for details see e.g. [1])). One can notice that polynomials $b_{n}$ satisfy the following 3-term recurrence:

$$
b_{n+1}(x)=x b_{n}(x)-b_{n-1}(x),
$$

with $b_{-1}(x)=0, b_{0}(x)=1$. First of all notice that if $\rho=0$ then we deal with trivial case. Hence let us assume that $0<|\rho|<1$. We have $\beta_{n}=0$ and $\hat{\beta}_{n}=1$ and further $C=\frac{\left(1-\rho^{2}\right)}{\rho^{2}}, D=-\frac{\left(1+\rho^{2}\right) y}{\rho}, E=\left(\frac{1-\rho^{2}}{\rho}\right)^{2}+y^{2}$. By direct computation we check that $\kappa_{1}=\kappa_{2}=-\rho y$ and $\lambda_{2}=\rho^{2}$. Now inserting all of the ingredients to equations (4.3)-(4.6) we see that $\kappa_{n}=-\rho y$ for $n \geq 1, \lambda_{n}=\rho^{2}$ for all $n \geq 2, \alpha_{n}$ $=0$, and $\hat{\alpha}_{n}=1$ for all $n \geq 1$. Thus $a_{n}(x)=b_{n}(x)-\rho y b_{n-1}(x)+\rho^{2} b_{n-2}(x)$ for all $n \geq 2$.

Now let us simplify calculations by assuming that the measure $d B$ and the polynomial $\left(x^{2}+D x+E\right)$ are symmetric which implies that polynomials orthogonal with respect to $d B$ (i.e. $b_{n}$ ) must contain only either even or odd powers of $x$. Hence coefficients $\beta_{n}$ are equal to zero for $n \geq 0$ and also that $D=0$. Consequently measure $d A$ must also be symmetric and by similar argument we deduce that coefficients $\alpha_{n}=0$ for $n \geq 0$. This results in the fact that coefficients $\kappa_{n}$ are also zero for all $n \geq 0$.

As a result we have the following Lemma which is in fact a corollary of the Proposition 1

Lemma 1. Suppose normalized, positive measures $d A$ and $d B$ are related to one another by the relationship:

$$
d A(x)=\frac{C}{x^{2}+E} d B(x)
$$

Let further respectively polynomial sequences $\left\{a_{n}\right\}$ and $\left\{b_{n}\right\}$ orthogonal with respect to these measures satisfy 3-term recurrence (1.1) and (1.2). With $\beta_{n}=0$ for $n \geq 0$. Then there exist a number sequences $\left\{\lambda_{n}\right\}$ such that

$$
\begin{equation*}
a_{n}(x)=b_{n}(x)+\lambda_{n} b_{n-2}(x), \tag{4.7}
\end{equation*}
$$

and $\alpha_{n}=0$ for $n \geq 0$. Moreover number sequence $\left\{\lambda_{n}\right\}$, satisfies the following second order recursive equation for $n \geq 3$ :

$$
\begin{equation*}
\lambda_{n+1}=\lambda_{n}+\hat{\beta}_{n-1}-\frac{\lambda_{n}}{\lambda_{n-1}} \hat{\beta}_{n-3} \tag{4.8}
\end{equation*}
$$

with $\lambda_{1}=0, \lambda_{2}=\hat{\beta}_{0}+E-C, \lambda_{3}=\hat{\beta}_{1}+E-\frac{E}{C-E} \hat{\beta}_{0}$.

Coefficients $\hat{\alpha}_{n}$ are given by relationship:

$$
\hat{\alpha}_{n}=\frac{\lambda_{n+1}}{\lambda_{n}} \hat{\beta}_{n-2}
$$

Proof. We apply assumptions to the system of equations 4.3 4.6) getting:

$$
\begin{aligned}
\lambda_{n+1}+\hat{\alpha}_{n-1} & =\lambda_{n}+\hat{\beta}_{n-1} \\
\hat{\alpha}_{n-1} \lambda_{n-1} & =\lambda_{n} \hat{\beta}_{n-3}
\end{aligned}
$$

from which we get (4.8). To get initial conditions we notice that $a_{2}(x)=x^{2}-\hat{\beta}_{0}+\lambda_{2}$ $=x^{2}+E+\left(\lambda_{2}-\beta_{0}-E\right)$, so from the relationships $\int_{\operatorname{supp} B} a_{2}(x) d A(x)=0$ and $\int_{\text {supp } B}\left(x^{2}+E\right) d A(x)=C$ we get $C+\left(\lambda_{2}-\beta_{0}-E\right)=0$. Now to get $\lambda_{3}$ we use relationship: $\int_{\operatorname{supp} B} a_{1}(x) a_{3}(x) d A(x)=0$, using on the way the fact that $a_{3}(x)=b_{3}(x)+\lambda_{3} x=x\left(x^{2}-\hat{\beta}_{0}\right)-\hat{\beta}_{1} x+\lambda_{3} x=x^{3}+x\left(\lambda_{3}-\hat{\beta}_{0}-\hat{\beta}_{1}\right)$ and that $\int_{\operatorname{supp} B}\left(x^{2}-\hat{\beta}_{0}\right)\left(x^{2}+E\right) d A(x)=0$. We have: $0=\int_{\operatorname{supp} B}\left(\left(x^{2}-\hat{\beta}_{0}\right)\left(x^{2}+E\right)+\left(\lambda_{3}-\right.\right.$ $\left.\left.\hat{\beta}_{1}-E\right) x^{2}+\hat{\beta}_{0} E\right) d A(x)=\int_{\text {supp } B}\left(\left(\lambda_{3}-\hat{\beta}_{1}-E\right)\left(x^{2}+E\right)+\hat{\beta}_{0} E-E\left(\lambda_{3}-\hat{\beta}_{1}-E\right)\right) d A(x)$ $=C\left(\lambda_{3}-\hat{\beta}_{1}-E\right)-E\left(\lambda_{3}-\hat{\beta}_{1}-E-\hat{\beta}_{0}\right)=0$.

We will briefly illustrate this Lemma by the following example.
Example 5 (Jacobi polynomials revisited). Let us consider the symmetric case i.e. assuming that parameters $\alpha$ and $\gamma$ are equal say to $a$. Then $\beta_{n}=0$ and $\hat{\beta}_{n-1}=\frac{n(n+2 a)}{(2 a+2 n-1)(2 a+2 n+1)}$. Parameters $C$ and $E$ are now equal to $-\frac{2 a}{2 a+1}$ and -1 respectively. Hence

$$
\begin{aligned}
& \lambda_{2}=\hat{\beta}_{0}+E-C=-\frac{2}{(2 a+1)(2 a+3)} \\
& \lambda_{3}=\hat{\beta}_{1}+E-\frac{E}{C-E} \hat{\beta}_{0}=-\frac{6}{(2 a+3)(2 a+5)}
\end{aligned}
$$

Besides one can easily check that the sequence $\left\{-\frac{n(n-1)}{(2 a+2 n-1)(2 a+2 n-3)}\right\}$ satisfies (4.8). So $\lambda_{n}=-\frac{n(n-1)}{(2 a+2 n-1)(2 a+2 n-3)}, n \geq 2$. Hence we have:

$$
J_{n}^{(\alpha-1, \alpha-1)}(x)=J_{n}^{(\alpha, \alpha)}-\frac{n(n-1)}{(2 a+2 n-1)(2 a+2 n-3)} J_{n-2}^{(\alpha, \alpha)} .
$$

In particular notice that for $\alpha=1 / 2$ we have $J_{n}^{(1 / 2,1 / 2)}(x)=U_{n}(x) / 2^{n}$ where $U_{n}$ are the Chebyshev polynomials of the second kind, while $J_{n}^{(-1 / 2,-1 / 2)}(x)=$ $T_{n}(x) / 2^{n-1}$ for $n \geq 2$ and $J_{n}^{(-1 / 2,-1 / 2)}(x)=T_{n}(x)$ for $n=0,1$, where $T_{n}(x)$, are the Chebyshev polynomials of the first kind. Besides $\left[-\frac{n(n-1)}{(2 a+2 n-1)(2 a+2 n-3)}\right]_{\alpha=1 / 2}$ $=-\frac{1}{4}$ and we end up with well known relationship between Chebyshev polynomials of the first and second kind:

$$
T_{n}(x)=\left(U_{n}(x)-U_{n-2}(x)\right) / 2 .
$$

Remark 6. Notice that we could have reached the result in the above mentioned example by applying the procedure described in Section $\mathbf{Q}$ twice once for monomial $1-x$ and then for $1+x$.

Remark 7. Notice also that one could invert relationship 4.7) and find connection coefficients of polynomials $\left\{b_{n}\right\}$ expressed in terms of polynomials $\left\{a_{n}\right\}$. Like in the setting of Corollary 1 they would be expressed in terms of products of coefficients $\left\{\lambda_{n}\right\}$ (in fact either only with odd or even numbers) and consequently obtain expansion similar 2.7) (in fact involving polynomials $\left\{b_{n}\right\}$ with even numbers).

### 4.1. Open problems.

- Is it possible to simplify equation (4.8) and reduce it to the first order recursive equation?
- Is it possible to simplify system of equations (4.3-4.6) and reduce it to the problem of solving system of the first order recursive equations?
- More generally is it possible to solve general system of equations presented in Proposition 1 of [14] or at least deduce more properties of coefficients $\left\{c_{n}^{(j)}\right\}_{n \geq 1,1 \leq j \leq r}$ not only that for $j>r$ they are zeros.
- Is it possible give some properties of connection coefficients between the two sets of orthogonal polynomials given the fact that orthogonalizing measures are related by the known relationship $d A(x)=F(x) d B(x)$ for functions $F$ different from the reciprocal of a polynomial. It seems possible to consider rational functions to start generalization.


## 5. Proofs

Proof of Theorem 11. Noticing that the proof of Proposition 1, iii) does not require the measures $d A(x)$ and $d B(x)$ to have densities we can apply its assertion and deduce that if positive, normalized measures are related by the relationship (2.1) then the polynomial sequences $\left\{a_{n}\right\}$ and $\left\{b_{n}\right\}$ orthogonal respectively with respect to these measures are related by (2.3). Hence sequence $\left\{\kappa_{n}\right\}$ exists and consequently we have $a_{n}(x)=b_{n}(x)+\kappa_{n} b_{n-1}(x)$. Remembering that sequences of polynomials $\left\{a_{n}\right\}$ and $\left\{b_{n}\right\}$ are orthogonal and satisfy the following 3-term recurrences:

$$
\begin{aligned}
a_{n+1}(x) & =\left(x-\alpha_{n}\right) a_{n}(x)-\hat{\alpha}_{n-1} a_{n-1}(x), \\
b_{n+1}(x) & =\left(x-\beta_{n}\right) b_{n}(x)-\hat{\beta}_{n-1} b_{n-1}(x) .
\end{aligned}
$$

So on one hand we have

$$
\begin{aligned}
x a_{n}(x) & =a_{n+1}(x)+\alpha_{n} a_{n}(x)+\hat{\alpha}_{n-1} a_{n-1} \\
& =b_{n+1}(x)+\left(\kappa_{n+1}+\alpha_{n} \kappa_{n}\right) b_{n}+\left(\alpha_{n} \kappa_{n}+\hat{\alpha}_{n-1}\right) b_{n-1}(x)+\hat{\alpha}_{n-1} \kappa_{n-1} b_{n-2}(x) .
\end{aligned}
$$

On the other we have:

$$
\begin{aligned}
x a_{n}(x) & =x b_{n}(x)+x \kappa_{n} b_{n-1}(x) \\
& =b_{n+1}(x)+\left(\beta_{n}+\kappa_{n}\right) b_{n}(x)+\left(\hat{\beta}_{n-1}+\kappa_{n} \beta_{n-1}\right) b_{n-1}+\kappa_{n} \hat{\beta}_{n-2} b_{n-2}(x)
\end{aligned}
$$

Hence we must have:

$$
\begin{aligned}
\kappa_{n+1}+\alpha_{n} & =\beta_{n}+\kappa_{n} \\
\alpha_{n} \kappa_{n}+\hat{\alpha}_{n-1} & =\hat{\beta}_{n-1}+\kappa_{n} \beta_{n-1} \\
\hat{\alpha}_{n-1} \kappa_{n-1} & =\kappa_{n} \hat{\beta}_{n-2}
\end{aligned}
$$

Now let us get $\alpha_{n}$ from the first of the equations

$$
\alpha_{n}=\beta_{n}+\kappa_{n}-\kappa_{n+1}
$$

We get further

$$
\hat{\alpha}_{n-1}=-\beta_{n} \kappa_{n}-\kappa_{n}^{2}+\kappa_{n} \kappa_{n+1}+\hat{\beta}_{n-1}+\kappa_{n} \beta_{n-1}
$$

So finally we have:

$$
\kappa_{n-1}\left(-\beta_{n} \kappa_{n}-\kappa_{n}^{2}+\kappa_{n} \kappa_{n+1}+\hat{\beta}_{n-1}+\kappa_{n} \beta_{n-1}\right)=\kappa_{n} \hat{\beta}_{n-2}
$$

dividing both sides by $\kappa_{n} \kappa_{n-1}$ we get:

$$
\kappa_{n+1}=\kappa_{n}+\frac{\hat{\beta}_{n-2}}{\kappa_{n-1}}-\frac{\hat{\beta}_{n-1}}{\kappa_{n}}+\beta_{n}-\beta_{n-1}
$$

Now notice that we can rearrange terms on both sides of this equation in the following way:

$$
\kappa_{n+1}+\frac{\hat{\beta}_{n-1}}{\kappa_{n}}-\beta_{n}=\kappa_{n}+\frac{\hat{\beta}_{n-2}}{\kappa_{n-1}}-\beta_{n-1}
$$

proving that quantity $\kappa_{n}+\frac{\hat{\beta}_{n-2}}{\kappa_{n-1}}-\beta_{n-1}$ does not depend on $n$ and is equal to $\kappa_{2}$ $+\frac{\hat{\beta}_{0}}{\kappa_{1}}-\beta_{1}$.

We can easily find this quantity by finding directly quantities $\kappa_{1}$ and $\kappa_{2}$.
Naturally we have $\kappa_{0}=1$. Remembering that $d B(x)=(d+c x) d A(x)$, that

$$
b_{n+1}(x)=\left(x-\beta_{n}\right) b_{n}(x)-\hat{\beta}_{n} b_{n-1}(x)
$$

and since $\int_{\operatorname{supp} A} a_{1}(x) d A(x)=0$ we must have

$$
1=\int_{\operatorname{supp} A} d A(x)=\int_{\operatorname{supp} A} \frac{C}{(D+x)} d B(x)
$$

Now since $a_{1}(x)=b_{1}(x)+\kappa_{1}$ we have

$$
\begin{aligned}
0 & =\int_{\operatorname{supp} A} \frac{C\left(b_{1}(x)+\kappa_{1}\right)}{(D+x)} d B(x) \\
& =C+\left(\kappa_{1}-\beta_{0}-D\right) \int \frac{C}{x+D} d B(x)=C+\kappa_{1}-\beta_{0}-D
\end{aligned}
$$

So

$$
\kappa_{1}=\beta_{0}+D-C
$$

To find $\kappa_{2}$ we use the fact that $a_{2}(x)=b_{2}(x)+\kappa_{2} b_{1}(x)$. Hence we have:

$$
\begin{aligned}
0 & =C \int_{\operatorname{supp} A} \frac{\left(b_{2}(x)+\kappa_{2} b_{1}(x)\right)}{(D+x)} d B(x) \\
& =C \int_{\operatorname{supp} A} \frac{\left(\left(-D-\beta_{1}+\kappa_{2}\right)\left(b_{1}(x)+\kappa_{1}-\kappa_{1}\right)-\hat{\beta}_{0}\right)}{(D+x)} d B(x) \\
& =C \int_{\operatorname{supp} A} \frac{\left(\left(D+\beta_{1}-\kappa_{2}\right) \kappa_{1}-\hat{\beta}_{0}\right)}{(D+x)} d B(x)=\left(\left(D+\beta_{1}-\kappa_{2}\right) \kappa_{1}-\hat{\beta}_{0}\right) .
\end{aligned}
$$

Hence we see that $\kappa_{2}+\frac{\hat{\beta}_{0}}{\kappa_{1}}-\beta_{1}=D$.

Proof of Proposition 1. Assuming that both sequences of polynomials i.e. $\left\{a_{n}\right\}$ and $\left\{b_{n}\right\}$ are orthogonal we have on one hand:

$$
\begin{aligned}
x a_{n}(x)= & a_{n+1}+\alpha_{n} a_{n}(x)+\hat{\alpha}_{n-1} a_{n-1}(x)= \\
= & b_{n+1}(x)+\left(\kappa_{n+1}+\alpha_{n}\right) b_{n}(x)+\left(\lambda_{n+1}+\alpha_{n} \kappa_{n}+\hat{\alpha}_{n-1}\right) b_{n-1}(x) \\
& +\left(\alpha_{n} \lambda_{n}+\hat{\alpha}_{n-1} \kappa_{n-1}\right) b_{n-2}(x)+\hat{\alpha}_{n-1} \lambda_{n-1} b_{n-3}(x) .
\end{aligned}
$$

and on the other:

$$
\begin{aligned}
x a_{n}(x)= & x\left(b_{n}(x)+\kappa_{n} b_{n-1}(x)+\lambda_{n} b_{n-2}(x)\right) \\
= & b_{n+1}+\left(\beta_{n}+\kappa_{n}\right) b_{n}(x)+\left(\hat{\beta}_{n-1}+\kappa_{n} \beta_{n-1}+X_{n}\right) b_{n-1}(x)+ \\
& \left(\kappa_{n} \hat{\beta}_{n-2}+\lambda_{n} \beta_{n-2}\right) b_{n-2}(x)+\lambda_{n} \hat{\beta}_{n-3} b_{n-3}(x) .
\end{aligned}
$$

Comparing expressions by $b_{n}, b_{n-1}, b_{n-2}$ and $b_{n-3}$ we get equations (4.3-4.6).

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