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Testing linear growth rate formulas of non-scale endogenous growth models

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Abstract Endogenous growth theory has produced formulas for steady-state growth rates of income per capita which are linear in the growth rate of the population. Depending on the details of the models, slopes and intercepts are positive, zero or negative. Empirical tests have taken over the assumption of exogenous population growth from the theoretical models and have mostly not distinguished steady-state results from transitional growth. In contrast, we assume (i) that there is two-way causality as in unified growth theory, and (ii) capture the steady-state property by a long-term relation in a series of vector-error-correction models allowing (iii) successively for more heterogeneity. The slope of the growth equations is positive in this setting. Intercepts are most frequently also positive, but almost equally often zero, and sometimes even negative. Results slightly favour fully- over semi-endogenous growth, and the slightly more frequent case is that long-run growth can remain positive if population stops growing. Zero or negative intercepts cannot be ruled out though.

JEL-codes: C33, O47. Keywords: Endogenous growth, population growth, panel times series estimation.

1. Introduction

Ever since the invention of the semi-endogenous growth model by Arrow (1962) and Phelps (1966) and its extension to micro-foundation and spillovers by Jones (1995) a major criticism has been that it would predict to have no growth in the absence of population growth (von Weizsäcker 1969). In contrast, Jones (1995) emphasizes that the number of engineers and scientists in R&D has increased strongly in recent years but the growth rate has not reacted and therefore semi-endogenous growth models should be favoured over fully-endogenous growth models. However, more recent evaluations of fully and semi-endogenous growth models favour the fully endogenous growth models from the perspective of emphasizing the time-series dimension using unit root and cointegration analysis as well as forecasts (Ha and Howitt 2007; Madsen 2008). Ha and Howitt (2007) emphasize that R&D as a share of GDP has been fairly constant and so have the TFP growth rates. From the perspective of Lucas' (1988) endogenous growth model, the education data of Gaessler and Ziesemer (2016) for the USA are not increasing for the period 1985-2009. Therefore, Jones' (1995) critique, based on data for engineers, would not hold when using their education data in the Lucas model. Even if education time shares would increase, one would have to check for an increase of the depreciation rate for human capital during the same period in order to see the net effect on growth. Moreover, in the closed and the open[2] economy versions of the

[*]We are grateful for useful comments from Theophile Azomahou, Alberto Bucci, Karl-Josef Koch, Joan Muysken, and Tania Treibich.

[2] See Frenkel et al (1996), Gaessler and Ziesemer (2016).

Lucas model, population growth and that of GDP per capita are positively related with a positive intercept in the solution, which implies positive growth in the absence of population growth. The intercept then represents institutional aspects which ensure positive growth even in the absence of resource growth (Ha and Howitt 2007). In contrast, some other endogenous growth models have the opposite slope or no intercept.[3] Prettner and Prskawetz (2010) though point out that the semi-endogenous type of models with positive slope and zero intercept is favoured by some authors more recently. This view gets some recent support from Kruse-Andersen (2017) for R&D models at the cost of neglecting human capital though. Others doubt the positive slope though: Strulik et al (2013) argue that "there is little empirical support for a positive association between population growth and productivity growth". All these stark contrasts in the views on slopes and intercepts raise two questions, (i) that of a positive, zero or even negative slope relating population growth and income growth and (ii) that of the existence of a statistically significant intercept.

2. Long-run growth formulas

Monopolistic competition models are slightly more complicated than the Lucas model briefly sketched above. The semi-endogenous growth model generates the long-run growth formula $g_y = (\lambda\text{-}v)g_n/(1\text{-}\gamma)$ with **$\gamma < 1$** as R&D spillover parameter, λ as percentage of non-duplication and v as the degree of difficulty of R&D (see Dinopoulos and Segerström 1999). The slope coefficient can have any sign. Without duplication, $\lambda=1$, and no difficulty, $v=0$, we get the well-known case of Jones (1995) as $g_y = g_n/(1\text{-}\gamma)$.[4] These equations have a zero intercept.

In the fully endogenous growth model of Howitt (1999) there is in addition a negative intercept. The steady-state growth rate In Howitt (1999) is $g = \sigma\lambda n$, with n as productivity-adjusted R&D expenditure, σ a parameter and λ a Poisson arrival rate, all related to vertical R&D. From Fig.1 in Howitt (1999) one can solve for $n = \frac{(1-\alpha+\sigma)g_{L/\psi(h*)}}{(1-\beta)(1+\frac{\alpha\sigma}{1-\alpha})} - \frac{r}{\lambda(1+\frac{\alpha\sigma}{1-\alpha})}$, with α as elasticity of production of capital, $1\text{-}\beta$ as marginal cost of horizontal R&D expenditure, ψ as intensive-form production function of horizontal innovation, r as the interest rate and g_L as population growth rate, and h^* the steady-state share of expenditure on research. Inserting

[3] An exception is Strulik (2005) where the intercept is positive and the slope can have any sign. He combines the Lucas model with that of varieties, including duplication and difficulty. Consequently, having a positive intercept in the growth formula is caused by the Lucas part of the model. We do not deny that there are other papers fitting into the scheme, but we have to be brief here.

[4] Note that for $\gamma<(=) 0$, steady-state growth rates should be equal or even lower than population or employment growth rates, which seems to be unrealistic for high-income OECD countries. For 1977-2011 the employment in full-time equivalents grows at one percent per year; for 2001-11 this is less than 0.5 percent. Since 1995 OECD population growth rates are below 0.8 percent.

the formula for n into that for g it becomes obvious that there is a negative intercept.[5] Insertion of the standard consumption function after solving it for r and then solving for g again does not change this qualitative result.

In an AK growth model, Dalgaard and Kreiner (2001) disaggregate K into a Cobb-Douglas function of two production factors H and A, and assume a positive savings rate for the change of both. The result is a slope of g_n of minus unity in case of a non-Benthamite utility function (no N_t multiplied to the per capita utility function) and a zero slope in the Benthamite case. In both cases they have a positive intercept. These cases can be collected as the following list of hypotheses for the relation between population growth and growth of income per capita.[6]

TABLE 2 Cases of long-run growth formulas

Hypothesis	slope	intercept
Lucas	positive	positive
Jones	positive	zero
Howitt	positive	negative
AK non Bentham	negative	positive
AK Bentham	zero	positive

Other case constellations may be possible but we only want to indicate that in principle every result for the slope or the intercept is possible according to the theoretical models.

When trying to test these hypotheses we have to take into account that the assumption of exogenous population growth in endogenous growth theory is a strong simplification. Income has an impact on population growth in rich and poor countries, which is taken into account in unified growth theory (Galor and Weil 1999) and has to be taken into account when evaluating non-scale models[7]. Whereas for large panels (including less rich countries than our panel) it is the level of income (with several lags though) that has an impact (Kelley and Schmidt 1995; Herzer et al 2012; Fosu et al 2016), the question here is posed for rich countries producing technical change, and therefore the income level is not an aspect of the discussion, but rather the structure of endogenous growth models is and thereby the growth rate of income or productivity is crucial. This implies two-way causality between the growth rates of per capita income and the population, g_y and g_N. We do not use TFP data because

[5] Insertion of the standard consumption function after solving it for r and then solving for g again does not change this qualitative result.
[6] Tournemain (2007) as well as Bucci and Raurich (2017) survey the relevant literature more broadly.
[7] The expression emphasizes the contrast with models that have the level of the population on the right-hand side of the formula for the solution of the growth rate as in Shell (1967) and others later.

the process of making them tends to impose a Cobb-Douglas function for output production, having unit elasticity of substitution, where in general many would prefer a lower one; however there is no agreement to a certain value below one. As Brander and Dowrick (1994) have pointed out it is important to have a dynamic system analysis for this interaction. Ha and Howitt (2007) use a simple error-correction model and favour the fully endogenous growth models based on analysis of unit roots, cointegration and forecasting for the USA. They do not analyze the empirics of the intercept though and they also do not estimate a dynamic model for only endogenous variables using lags, both of which we will do here.

3. Estimation: Methods and results

We consider the growth rates of per capita GDP and population of 16 OECD countries for the period 1960-2014. Pooled mean group (PMG) estimators assuming a common coefficient in the long-run relation for the two causality directions estimated separately results in long-term relations of $g_y = -0.8g_n$ (Table 2, regression 1) and $g_N = 0.27g_y$ (Table 2, regression 2)[8]. They are very much different from each other and indicate two-way causality with opposite signs. The variables are demeaned for time and period fixed effects before running the regressions (1)-(3) and (5). The first of these equations can be seen as an estimate of the equation used as framework by Ha and Howitt (2007) with TFP as endogenous variable. Also, the first of these equations is very similar to the cross-section results in Strulik et al. (2013) using TFP growth rates. But cross-section analysis does not take into account that in many countries growth rates of TFP and population are both falling during the after-war period. This latter fact suggests a positive correlation which we find in the second equation above and also if we use $g_n(-20)$ in the first equation resulting in a long-run relation of $g_y = 0.67g_n(-20)$ (not shown) with a large loss of observations.[9] Therefore, in order to find a long-term relation, we have to use an econometric method that takes into account two-way causality. Vector-error-correction models (VECM) are doing this. VECMs have also the advantage that long-term relations may reflect steady-state results although economies are not yet in the steady state at least in the beginning of the estimation period. Lagged impacts are used to estimate the model, which is an aspect which Ha and Howitt

[8] These regressions should neither be mixed up with those regressing population growth or fertility on (several lags of) the log of GDP per capita (see Ahituv (2001), Herzer et al (2012) and Fosu et al (2016)) nor with growth regressions which have a lagged dependent variable (Li and Zhang 2007). Both are made for out-of-steady-state purposes and growth regressions are mostly not made for endogenous growth models.

[9] Strulik et al (2013) in their Figure 2 show a positive correlation before 1920 and after 1970, and a negative correlation in between. The debates of modern growth theory focus on the phase since 1950 or 1960, because before this time education and invention were limited to a small part of the population. Ziesemer (2016) uses a cubic specification for labour force growth in a growth regression for a large panel of countries producing a negative effect only if labour growth is stronger than 2.45 percent as it is realistic for some African countries.

(2007) regret to omit. We estimate three VECMs for our sample of 16 countries allowing for successively more heterogeneity. The first is

$$d(g_{yt}) = \alpha_1 [g_{y\,t-1} - \beta g_{n\,t-1}] + \gamma_{11} d(g_{y\,t-1}) + \gamma_{12} d(g_{n\,t-1}) + \gamma_{13} d(g_{y\,t-2}) + \gamma_{14} d(g_{n\,t-2}) + \gamma_{15} d(g_{y\,t-3}) + \gamma_{16} d(g_{nt-3}) + \gamma_{17} d(g_{y\,t-4}) + \gamma_{18} d(g_{n\,t-4}) + u_{1t} \qquad (1a)$$

$$d(g_{nt}) = \alpha_2 [g_{y\,t-1} - \beta g_{n\,t-1}] + \gamma_{21} d(g_{y\,t-1}) + \gamma_{22} d(g_{n\,t-1}) + \gamma_{23} d(g_{y\,t-2}) + \gamma_{24} d(g_{n\,t-2}) + \gamma_{25} d(g_{y\,t-3}) + \gamma_{26} d(g_{n\,t-3}) + \gamma_{27} d(g_{y\,t-4}) + \gamma_{28} d(g_{n\,t-4}) + u_{2t} \qquad (1b)$$

All data are pooled and the covariance matrix is $E(u_t u'_t) = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix}$ (see Canova and Ciccarelli 2013). This 2x2 covariance matrix means that no country interaction is taken into account because the data are pooled. The second version estimates jointly 16 VECMs, one per country *i*:

$$d(g_y)_{i\,t} = \alpha_{1i} [g_{y\,it-1} - \beta g_{n\,it-1}] + \gamma_{11i} d(g_{y\,it-1}) + \gamma_{12i} d(g_{n\,it-1}) + \gamma_{13i} d(g_{y\,it-2}) + \gamma_{14i} d(g_{n\,it-2}) + \gamma_{15i} d(g_{y\,it-3}) + \gamma_{16i} d(g_{n\,it-3}) + \gamma_{17i} d(g_{y\,it-4}) + \gamma_{18} d(g_{n\,it-4}) + u_{1it} \qquad (2a)$$

$$d(g_n)_{it} = \alpha_{2i} [g_{y\,it-1} - \beta g_{n\,it-1}] + \gamma_{21i} d(g_{y\,it-1}) + \gamma_{22i} d(g_{n\,it-1}) + \gamma_{23i} d(g_{y\,it-2}) + \gamma_{24i} d(g_{n\,t-2}) + \gamma_{25i} d(g_{y\,it-3}) + \gamma_{26i} d(g_{n\,it-3}) + \gamma_{27i} d(g_{y\,it-4}) + \gamma_{28i} d(g_{n\,it-4}) + u_{2it} \qquad (2b)$$

All coefficients are country-specific with the exception of β, which is constrained to be identical over countries and time as in the pooled mean-group (PMG) estimator. The covariance matrix then has format $Nk \times Nk = 32x32$, as there are $N = 16$ countries with $k=2$ variables and equations each (see Groen and Kleibergen 2003, eq. (6)). This approach can take into account interaction between the residuals of the countries.

The third model differs from (2a, b) in that it leaves also the β_i free, except for being the same in the two equations of the VECM of each country, of course.

In order to take fixed effects for countries and periods into account in the long-term relation of vector-error-correction model (1a,b) we subtract again the country and period specific averages of each variable from the variable itself and add the sample mean (see Greene 2008, p.198). Therefore the equations above have no explicit constants, which will be retrieved from the long-term relation though. The double demeaned variable for population growth has individual and common unit roots, with and without individual trends in combinations with SIC, AIC or HQC. Without demeaning there is a common unit root but mixed evidence for individual unit roots. The growth rate of the GDP per capita never shows a unit root in all these combination, but it is well-known that they often have near-unit roots.

The double-demeaned variables are cointegrated according to the standard panel cointegration tests of Pedroni, Kao, and Johansen-Fischer.

The result obtained from maximum likelihood estimation of (1a, b), a VECM with four lags (because the underlying VAR has five lags), is a slope of 0.62 and an intercept of 1.87 plus country-specific deviations in the range of (-0.87, 1.03) leading to a range of growth rates of g_y for $g_n = 0$ in the interval from (1.0, 2.9) (see Table 2, regression 3). Other estimation methods lead to similar results; see notes to Table 2. To get an idea of the statistical significance of the intercept we use the VECM without fixed effects transformation of the data. The underlying VAR has three lags according to all criteria and the VECM yields the

TABLE 2	**Error-correction estimates for growth rates income and population**						
Regression		(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable(s)		d(gy)	d(gn)	d(gy), d(gn)	d(gy), d(gn)	$d(gy)_i$, $d(gn)_i$	$d(gy)_i$, $d(gn)_i$
long run							
dependent variable		gy	gn	gy	gy	gy	
regressor	gn	-0.8	-	0.62	0.63	1.29	1.23 (i)
		(-3.46)	-	(1.9)	(1.95)	(3.255)	(-0.64) (k)
	gy	-	0.275	-	-	-	
			(3.5)				
	constant	-	-	1.87+(-0.87,1.03)	1.8	1.4 +(-1.45, 1.23)	0.195 (g)
					(-6.45)		(-0.157) (k)
short run							
adjustment coeff.		-0.72	-0.086	-0.47, 0.0675	-0.42, 0.035	-0.39, 0.06 (f)	0.14, -0.018 (h)
		(-17.5)	(-4.68)	(-8.28), (7.7)	(-10.2), (7.28)	(-2.227), (2.99) (k)	(0.12),(-0.157) (k)
regressors							
Lags (coeff. or no)	D(gn)	0.87	2	4	2	2	2
		(-1.61)					
Lags (coeff. or no)	D(gy)	-	1	4	2	2	2
Countries		16	16	16	16	16	16
Period		1962-2014	1963-2014	1966-2014	1964-2014	1965-2014	1965-2014
Observation		828	814	764	796	1560	
Method		PMG	PMG	FIML	FIML	3SLS	3SLS
		ARDL(1,1)	ARDL(3,1)	VECM	VECM	VECM	VECM
Log likelihood		-1561.246	347.6567	-1526.6, -97.38	-1833.9, -136.6	-	-
Fixed effects		countries	countries	countries	none (d)	countries	countries
		periods (a)	periods (b)	periods (c)		periods (e)	
p (adj Q) (j)		-	-	0.16; 0.55	0.04, 0.39	0.16, 0.68	0.066, 0.32

t-values in parantheses

(a) Fixed effects via demeaning; adjustment coefficents range between (-1.02, -0.36; highest p=0.0001);
coefficients for d(gn) range from -2.1 to 4.77. AIC for lag selection.

(b) Fixed effects via demeaning; AIC for lag selection.
adjustment coefficients range between -0.26 and 0.088 with highest p-value =0.0019

(c) Fixed effects via demeaning; covariances are σ(1,1) = 3.185; σ(2,2) = 0.0755; σ(1,2) =σ(2,1) =- 0.24. Boswijk (1995) for s.e. of long run coeff. .
Lag length choice according to lag length criteria, stability test, and LM and Portmanteau serial correlation tests.
Intercept of 1.868 plus country-specific deviations in the range of (-0.87, 1.03)

(d) Lag length of VAR is three for all criteria. Boswijk (1995) for s.e. of long run coeff. .
Covariances are σ(1,1) = 5.87; σ(2,2) = 0.0825; σ(1,2) = σ(2,1) = - 0.055.

(e) Fixed effects via demeaning; lag length fixed at 2; long term coefficient constrained to be identical for all countries;
adjustment coefficients averaged over equations of 16 countries; other coefficients unconstrained. Covariance matrix is 32x32.
Portmanteau test for null of no serial correlation has p-values for adj Q-stat (see Lüthkepohl 2005) between 0.16 and 0.68.

(f) average over first and second set of equations (20a), (20b).

(g) average across countries with seven significantly positive, three significantly negative and six insignificant results for the intercept.

(h) average across countries for first and second set of equations.

(i) average over values for 16 countries.

(j) lowest and highest p-value for 12 lags in the Portmanteau test for 'no serial correlation' hypothesis (see Lüthkepohl 2005).

(k) the variance of a mean group estimator is obtained as the sum over all elements in the covariance matrix of the averaged coefficients.
See Davidson and McKinnon (2004), formula (3.68).
Division by 256 and taking the square root yields the standard error that can be used to divide the coefficient to get the t-value.

result $g_y = 0.63g_N + 1.81$ with t-values of 1.95 for the slope and 6.44 for the intercept Table 2, regression 4; it also indicates that the impact of fixed effects is limited although they could partly control for non-representative years or countries. In sum, slope and intercept are positive, statistically significant and economically of reasonable order with and without fixed effects.[10] This preliminary result is in line with the Lucas type of models and not with the others listed above. By implication, if population growth goes to zero we will still have a growth rate of 1.8 percent as an average across the sixteen countries of our panel. The use of lags above takes into account the common serial correlation of the regressors. This would cause a bias in the estimated coefficient in the case of common adjustment coefficients when common serial correlation is present but not taken into account in the estimation as shown by Pesaran and Smith (1995), equations (2.6-8; A.25). The essence of estimating system (2a, b) is (i) to take into account heterogeneity when these coefficients are not common to all countries and (ii) to estimate the equations for each country, and (iii) to take into account the relation between the residuals of the different countries (Groen and Kleibergen 2003). Moreover, the lagged dependent variables may suffer from the Nickell bias when T is small and therefore we use lags as instruments for all variables. We use the three-stage least squares estimator, which combines instruments and the seemingly-unrelated regression estimate of contemporaneous correlation dealing with cross-section dependence. The result for the PMG estimator using again the double demeaned variables (Table 2, regression 5) is a slope of 1.29 and an overall constant of 1.4, and country fixed effects in the interval of (-1.45, 1.23), implying for one country that the growth rate for $g_n = 0$ is zero indeed, but positive for all others. Regressions (3)-(5) would clearly favour the Lucas model. However, the PMG estimator of the slope may suffer from heterogeneity bias.

Jusélius et al (2014) suggest separate country-by-country estimation, which has the advantage of determining the adequate lag length per country, but the interaction of growth between the countries is not taken into account. This interaction may be stronger among the OECD countries of our sample than the developing countries they consider. We estimate 16 VECMs jointly, at the cost of assuming two lags for all countries. Three-Stage-Least-Squares estimation (including SUR, taking into account contemporaneous correlation of the residuals) with all coefficients flexible (Table 2, regression 6) yields an average slope of 1.23. We attribute the insignificance of the slope parameter to heterogeneity.[11,12] For the intercept we

[10] Both VARs are stable. Non-linear spillover effects can in theory lead to u-shaped or hump-shaped effects of population growth rates (Diwarkar and Sorek 2017). Depending on the education policies and the value of the population growth rate itself there can be positive or negative impacts of exogenous population growth rates on income growth rates for constant policies in theoretical models (Prettner 2014).

[11] According to Baltagi (2006) pooled estimation seems to be much more robust than when allowing for heterogeneity. Moreover, according to our knowledge the properties of PMG and MG estimators have not yet

get a mean of 0.2, with seven significantly positive country-specific effects supporting Lucas, three significantly negative ones supporting Howitt, and six insignificant results supporting Jones' semi-endogenous growth view if coefficients are put to zero. This supports fully-endogenous growth theory because there are ten cases of non-zero intercepts. Among the full-endogenous growth cases the Lucas model dominates in the sense that the largest number of cases has a significantly positive intercept.[13] An implication of this is that labour time shifting policies and structural changes such as those in the rate of population growth, the rate of depreciation of the human capital function or the Frisch elasticity for labour in the utility function have permanent effects. Moreover, growth can also remain positive if population growth goes to zero. But there are also cases supporting Jones (1995) and Howitt (1999), where those with insignificant intercept are almost as frequent as those with a positive one. In the case of a negative intercept sufficiently strong population growth is needed to outweigh the negative intercept constituted by interest costs or consumption growth.

Overall, regressions (3)-(6) support the positive slope coefficients of population growth. The results for the intercept in regressions (3)-(5) support Lucas more than the others because intercepts are positive. But under full heterogeneity in regression 6 neither the Lucas model nor those of Jones (1995) and Howitt (1999) can be ruled out when tests in heterogeneous panels are based on testing the slope and intercept of steady-state growth formulas for endogenous growth in VECMs where the intercept represents the growth in the absence of population growth.

4 Conclusion

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been investigated for the case of endogenous regressors (see Pesaran and Smith (1995) and Pesaran (2015) for the case of an exogenous regressor).

[12] The slope coefficients of the last two regressions with 32x32 covariance matrix in Table 2 are twice as high as those with 2x2 covariance matrix. Using the GMM method with heteroscedasticity and autocorrelation consistent coefficients and standard errors (HAC) or Maximum-likelihood leads to a 'near singular matrix' warning, indicating that the determinant of the inverted matrix in the estimator is close to zero. Therefore we cannot use the iterative procedure suggested by Groen and Kleibergen (2003), which suggests using ML to estimate the covariance matrix and using that in SURE or GMM estimation. This is less extreme in the 3SLS estimates but may be the reason for the higher estimates. The significance of the slope parameter in regression 6 is low, indicating either that the heterogeneity is strong or we are in the curse of dimensionality because of a low number of observations. Adding common factors yields a 'near singular matrix' warning more often and do would time dummies for structural breaks.

[13] Strulik's (2005) and Bucci's (2008) synthesis of Lucas and the variety models can be reconciled with more than one of these outcomes. Time-series studies compared to cross-country studies give less support to semi-endogenous growth (Madsen 2008). Studies without panel heterogeneity put a bit more weight to the semi-endogenous growth models (see Neves and Sequeira 2017). Our result provides also empirical support for Cozzi's (2017) hybrid model, which is based on a linear combination of the semi-endogenous and a fully endogenous growth model, leading to results of the latter when population growth is low as it is in our sample.

We have tested endogenous growth models, which generate a linear formula of per capita income growth and population growth. The crucial step for the empirical work is to give up the simplifying assumption of growth models that population growth is exogenous. When population growth is endogenous and two-way causality is allowed for, a vector-error-correction approach shows that the relation between growth rates of income per capita and the population is positive. Intercepts are more frequently positive or negative than zero, favouring fully versus semi-endogenous growth. In the case of positive intercepts growth can be permanently positive even if population growth is zero. However, we cannot exclude the cases where population growth has to be positive to continue growing.

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