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Trend breaks in the research and development process

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This work examines the behaviour of the input and output measures of the R&D process in the United States, Germany, France and the United Kingdom, in the second half of the 20th century. The researcher and idea stock series can be construed as stationary fluctuations around a trend function, with a main breakpoint at the end of the 1960s. All the countries exhibit slower growth after their last breaks that during the decades preceding its first breaks. In this connection, the United States and Germany appear to represent the end points in the range of incidence.

I. Introduction

Many studies have documented a slowing down of productivity growth in Organization for Economic Co-operation and Development (OECD) countries, around the early 1970s and early 1980s. This being the case, one might expect a certain synchrony between the behaviour of output per worker, on the one hand and certain indicators of technological progress, on the other. Layton and Banerji (2003, pp. 1790–1792) noted that cyclical co-movements of the key coincident indicators characterise business cycles. For Romer (1990), the advance of technical progress depends on the discovery of new ideas. Researchers whose work is devoted to research and development (R&D) and idea stock activity, all other things being equal, determine total factor productivity (TFP) growth. By linking idea stock with TFP, Jones (1995, 2002) transformed the function of production for ideas into a technical progress function.

According to Keely and Quah (1998), R&D is a readily identifiable factor input for knowledge production in many technology-driven industries. A look back over the past decades reveals a decline in R&D growth rates that begins in the mid-1960s, 'the timing' being 'appropriate for declining productivity growth 5–10 years later' (Griliches, 1994, p. 2). This view is strengthened by the fact that the share of gross national product (GNP) devoted to R&D shows simultaneous signs of stagnating. As Verspagen (1996) points out and as Table 1 illustrates for the G-5, there appear to be huge differences (in terms of R&D spending) between the OECD countries. The USA and Switzerland started out as the leading countries in this respect, but during the 1970s and 1980s certain major European nations, also accompanied by Japan, caught up.

In this article, our goal is to provide a characterization of the takeoffs and slowdowns observed in input and output measures of R&D in the United States, Germany, France and the United Kingdom. A sequential methodology is applied to test for breaks in the number of researchers and in the idea stock, which introduces the possibility of examining the long-run behaviour of growth rates. The testing procedure covers the period between 1950 and 2001. The estimates bear out the perception of a slowdown in R&D process, although they bring forward the date of change. The four countries mentioned experience a trend and level break in the researcher series for the mid-1960s, with a slight variation in break year dates. The results as a whole also

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Table 1. Total R&D expenditures as a fraction of GDP

Year	USA	GER	FRA	JAP	UK
1963		0.014	0.016	0.015	
1967	0.021[a]	0.018	0.021	0.016	0.015[a]
1970	0.027	0.021	0.019	0.018	
1975	0.023	0.022	0.018	0.020	0.013[a]
1981	0.025	0.024	0.019	0.023	0.024
1986	0.029	0.027	0.022	0.027	0.023
1990	0.028	0.027	0.024	0.031	0.022
1995	0.025	0.026	0.023	0.030	0.020
2001	0.028	0.025	0.022	0.031	0.019
Average	0.026	0.021	0.019	0.022	0.019

Sources: OECD (various years) *Main Science and Technology Indicators*; Verspagen (1996).
Notes: [a]Business R&D expenditures as a fraction of GDP.

corroborate the thesis of new ideas slowdown, in the middle of the 1960s (coinciding, moreover, in the United States with the first oil crisis). The United States, at the top and Germany, at the bottom, represent the extremes in the range. Both statistical procedures allowing for two shifts and multiple structural change methods work out quite similar results.

The rest of the article is organised as follows. The next section describes the data and discusses measurement issues. In the third section, a time frame is spelt out to detect the presence of some breaks and their impact. The fourth section focuses on the timing of the breakpoints and assesses for the economic implications. Finally, the fifth section offers some concluding remarks.

II. Data

According to Romer's (1990) model, the cumulative stock of knowledge used to produce output, A, corresponds to the number of ideas invented over the course of the history until time t. In Jones' (2002) article, this is the first factor on the right side of the aggregate production function:

$$Y_t = A_t^{\sigma} K_t^{\alpha} H_{Yt}^{1-\alpha} \tag{1}$$

where K is physical capital and H_Y is the total quantity of human capital employed to produce output. It assumes $0 < \alpha < 1$ and $\sigma > 0$. In practice, A_t is measured as multifactor productivity in Equation 1. The accounting exercise is conducted in the same spirit as Solow's classic growth accounting model. (For data sources, see Appendix A).

On the other hand, effective research effort made by a country, H_A, is the weighted sum of researchers where the weights adjust for human capital:

$$H_{At} = \sum h_t^{\theta} L_{At} \tag{2}$$

In this equation, L_A is the number of researchers, h is human capital per person and $\theta \geq 0$. Scientists and technicians are viewed by the OECD as the central element within the research and development system. In accordance with the observations made by Bils and Klenow (2000, p. 1162) in relation to human capital, national scientists may both speed up the *adoption* of technology and also be necessary for technology *use*.

We are well aware of the potential problems caused by possible inadequacies presented by the data used to carry out the analysis. In this respect, idea stock (the residual of the production function) measures all other sources not taken into account by the growth rates of conventional inputs (Atella and Quintieri, 2001, p. 1387). On the other hand, the series for numbers of researchers appears to be more reliable, though certain considerations will have to be borne in mind (Romer, 2000, p. 21). To provide a rough empirical measure of H_A, we will assume that $\theta = 0$ in Equation 2. Nonetheless, 'measured R&D is the only data we have and it probably represents a reasonable benchmark provided these caveats are kept in mind' (Jones, 2002, p. 226). Indeed, any other indicator one might choose would certainly be accompanied by its own peculiar disadvantages. For example, scholars like Griliches (1990) have laboured long in their endeavours to measure patents, without coming up with any convincing outcome.

III. The Time Series Framework

This section lays briefly out the model and statistical procedure, allowing for two shifts in the deterministic trend at two distinct unknown dates. The reader is referred to Perron (1989, 1997), Banarjee *et al.* (1992), Zivot and Andrews (1992), Lumsdaine and Papell (1997), Vogelsang and Perron (1998), Ben-David and Papell (1995, 2000) and Atkins and Chan (2004) for further details. It is possible to think of y_t as being the sum of a deterministic component TD and a stochastic component Z_t,

$$y_t = TD_t + Z_t \tag{3}$$

where TD is linear in time t,

$$TD_t = \mu + \beta t \tag{4}$$

Once the unit root hypothesis has been rejected, the analysis focuses on the timing of the breakpoints and their severity. Our objective is to test for possible multiple structural changes in long-term output (logarithm of the stock of ideas and of researchers). The null hypothesis of no structural change is that μ and β are constant over the span of the data, whereas the alternative allows for one or more simultaneous changes in both the intercept and the slope. First, the null hypothesis of no structural change is tested, within a framework in which the break years are not exogenously predetermined, but where a process that endogenises the search is used. Sen (2004, p. 2026) shows that 'use of the mixed model will yield more reliable estimates of the break-date'. So the test for trending data involves regressions of the following form:

$$y_t = \mu + \sum_{i=1}^{m} \theta_i DU_{it} + \beta t + \sum_{i=1}^{m} \gamma_i DT_{it} + \sum_{j=1}^{k} c_j t_{t-j} + \varepsilon_t \tag{5}$$

The period in which a change takes place in the trend function parameters is identified as T_{Bi}. The break dummy variables take the following values: $DU_{it} = 1$ and $DT_{it} = t - T_{Bi}$ if $t > T_{Bi}, 0$ otherwise. The equation is estimated sequentially for all possible pairs (T_{B1}, T_{B2}), where $T_{Bi} = 2, \ldots, T-1$, $i = 1, 2$ and T is the number of observations after adjusting for lag length k. $C(L)$ is a lag polynomial of known order k.

For each choice of T_{Bi}, the value of the lag length k is established following the criterion employed by Campbell and Perron (1991). This is a recursive method, where an upper bound k_{max} is set *a priori*. If the last included lag is significant, choose the upper bound; otherwise, a unit reduces k. If there is no significant lag, set $k = 0$. We set the upper bound on k equal to 8 and the criterion of significance of the last lag statistic is set at 1.6, corresponding to 10% of the asymptotic normal distribution. The $\sup F_t$ statistic is the maximum (among all the possible trend breaks) of twice the standard F-statistic to test $\theta_1 = \gamma_1 = 0$. The null hypothesis of no structural change is rejected if it exceeds the critical value.

Once T_{B1} has been fixed in the manner indicated above, the Equation 5 is estimated for each potential break year (T_{B2}), calculating the statistic $\sup F_t$ as described. The procedure now consists of testing the null hypothesis of a one-break, as against a two-break alternative, subject to the constraint that the second break be separated from the first by a gap of at least 5 years. The possibility of more break points may be investigated, adding additional dummy variables to the equation. In this context, slowdown is to be understood as a statistically significant negative break in the trend function of the growth process. Recession, in contrast, is defined as a severe slowdown, whereby the pre-break growth rate is positive and the post-break rate is negative (Ben-David and Papell, 1998, p. 564).

We start by estimating regressions for a flexible model, allowing for multiple breaks, both in the slope of the trend function and in the intercept. If the DU_{it} and DT_{it} t-statistics are significant for a certain T_{Bi}, we register the results of the complete model; otherwise the nonsignificant variable is eliminated and we proceed to re-estimate models that admit breaks in the slope ($\theta_i = 0$) or in the intercept ($\gamma_i = 0$). So how does a break in the trend function affect steady state growth? If $y(t)$ has a stationary trend, it asymptotically approaches to a steady state growth path. Then, using the coefficients estimated from (5), the balanced growth rates converge for each country in the final period of the sample to the constant values:

$$\lim_{t\to\infty} \Delta y = \frac{\beta}{1 - \sum_{j=1}^{k} c_j} \tag{6}$$

or with

$$\lim_{t\to\infty} \Delta y = \frac{\beta + \sum_{i=1}^{m} \gamma_i}{1 - \sum_{j=1}^{k} c_j} \tag{7}$$

when the coefficients of the dummies registering the trend are included. From Equations 6 and 7 we gather that a change in level (θ_i) has an influence on stocks (of researchers and/or ideas), but not on growth rates. Whereas a trend break (γ_i), when there is stationarity, will have an impact on the steady state growth path.

IV. Trend Breaks and Steady State Growth

The main results, obtained by applying Equation 5, are presented in Table 2. In general, the data from the researcher and scientist collectives match up well with our intuition (panel A). Whilst expressing natural reservations, given a sample of this size, the process of estimation provides evidence of trend breaks. Using critical asymptotic values, the null hypothesis of no-break is rejected at a level of 5% in the United States and France. The decision is not so clear for Germany and Great Britain, although the value of the statistic (16.15 and 16.18) makes it possible to reject the null at a level of 10%.

It is interesting to observe the T_B break years involved here. In all the countries, they are located around the mid-1960s: France in 1966, the

Table 2. Sequential trend break tests

Country	Break	Year	Sup F_t	k
(A) Researchers and scientists				
United States	1	1967	18.49	6
Germany	1	1989	16.15	8
	2	1963	13.21	2
France	1	1966	22.48	4
	2	1980	29.29	4
United Kingdom	1	1968	16.18	2
(B) Idea stock				
United States	1	1966	21.61	6
	2	1973	14.64	1
Germany	1	1966	24.00	6
United Kingdom	1	1962	18.93	1
Critical values				
Breaks under hypothesis				
Null	Alternative	1%	5%	10%
0	1	23.74	17.85	15.34
1	2	21.12	16.49	14.15
2	3	20.42	15.59	13.76

Notes: The arrangement of years represents the order in which the breaks were found. Critical values from Ben-David and Papell (2000). Results may be conditioned by the fact that the critical values used are valid for $N=120$ sample.

United States in 1967 and Great Britain in 1968. Only Germany 'jumps the gun', its change occurring in 1963; although this is conditioned by the fact that the sup F_t statistic proves significant at a level of 10%. In all cases the estimation processes identify reductions in the trend function slope, i.e. there is a slowing-down. In the United States, there is additionally a drop in the intercept or, in other words, recession. (Appendix B records the coefficients and t-statistics in their totality.) The results suggest a high degree of coincidence in the development of the research infrastructure. At the end of the 1960s a deceleration was produced in the growth rate of this collective, anticipating the end of the 'golden age' of the western economies. The results coincide with those of Ben-David *et al.* (2003, p. 311), whose findings are that more than half of the countries they analysed experienced one of their breaks in 1955 or later, while some did so in the 1970s. Harvey and Mills (2005, p. 174) also provide strong evidence of the existence of a common business cycle among these countries.

As well as this generalized breakdown in the second half of the 1960s, in Germany, 1989 is the epitome of another breakpoint. The series of researchers is characterized by what seems to be a peak, followed by a swift return to the growth path prior to the break. As for France, the series climbs a rung in 1980 and embarks on a path with a somewhat steeper slope, but not enough to imply a trend change.

The results in Table 2 (panel B) are in accordance with the thesis of research intensity deceleration, between the mid-1960s and mid-1970s. Notwithstanding, the conclusions are not now as evident as those that were extracted from the researcher series. On the one hand, the null is conclusively rejected in the United States and Germany at a 5% level of significance, in favour of the alternative of stationarity accompanied by trend break in the 1960s. But, on the other hand, the estimation processes do not permit rejection of the null hypothesis of an absence of breaks in France and the situation in Great Britain is limited to an upwards change of level.

Figure 1 plots the logarithmic representation of the researcher and scientist series and Fig. 2 does the same in relation to idea stock. In both cases, the series projected are obtained by extrapolating the first pre-break growth paths. It can be easily noted that the actual paths, marked with a continuous line, are situated significantly below the extrapolations (subsequent to the break), depicted by a broken line.

How deep do the changes go? The crisis of the 1960s signals the end of the period of high growth that followed the post-second world war period; and a return to what seems to have been the new path of long-term growth in the western economies (Ben-David *et al.*, 2003, p. 312). All the γ_i, the coefficient of the dummy that registers trend change, are negative, though of a very different value. Two subgroups are easily identifiable in the sample: on one side, the United States and Great Britain, with around half a percentage point ($\gamma=-0.6\%$); on the other, Germany and France, whose average is higher than 1% point ($\gamma=-1.11\%$). The United States, at the top and Germany, at the bottom, represent the extremes in the range. The United States is the only country that, as the slope falls, experiences a simultaneous drop in level ($\theta_{1,\mathrm{US}}=-0.049$). When we turn to Germany, that country experienced the reunification of 1989 as a deceleration of similar importance to the slowdown in the 1960s, taking the shape of a new downturn ($\gamma_{1,\mathrm{GER}}=-0.012$).

Occurring in 1966, the break in the series of ideas (Table B2) took on dimensions in the United States similar to the above-mentioned researcher series trend break ($\gamma_{1,US}=-0.003$), while it had a much greater impact in Germany ($\gamma_{1,\mathrm{GER}}=-0.009$). Furthermore, there was a level break in the United Kingdom ($\theta_{1,\mathrm{UK}}=0.032$), in 1962 and another in the US ($\theta_{2,\mathrm{US}}=-0.034$), coinciding with the first oil crisis, in 1973 (Jiménez and Sánchez, 2005).

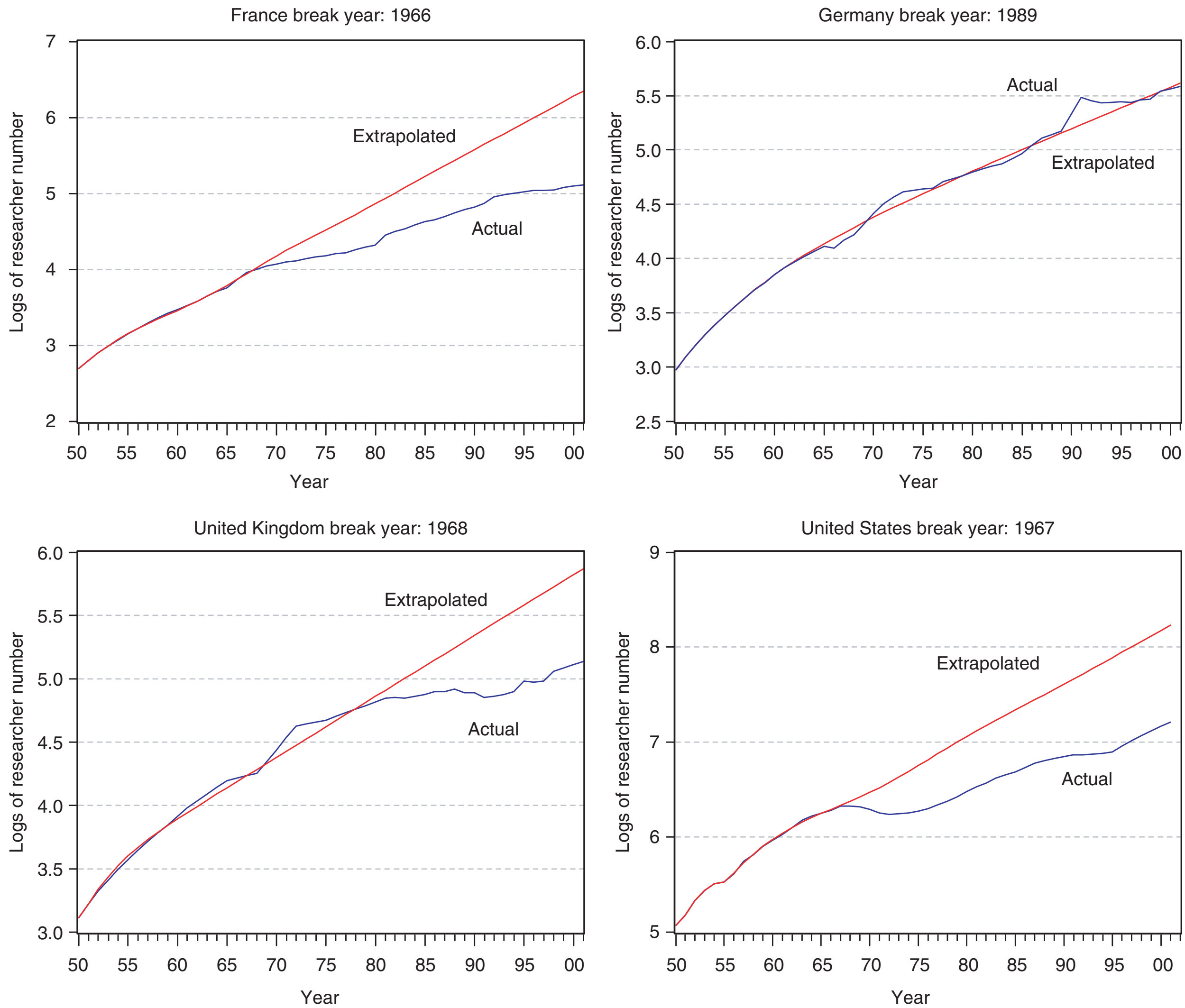

Fig. 1. Slowdown in R&D series: 1950–2001. Trend break years are above the panels. The scales of the panels are not the same

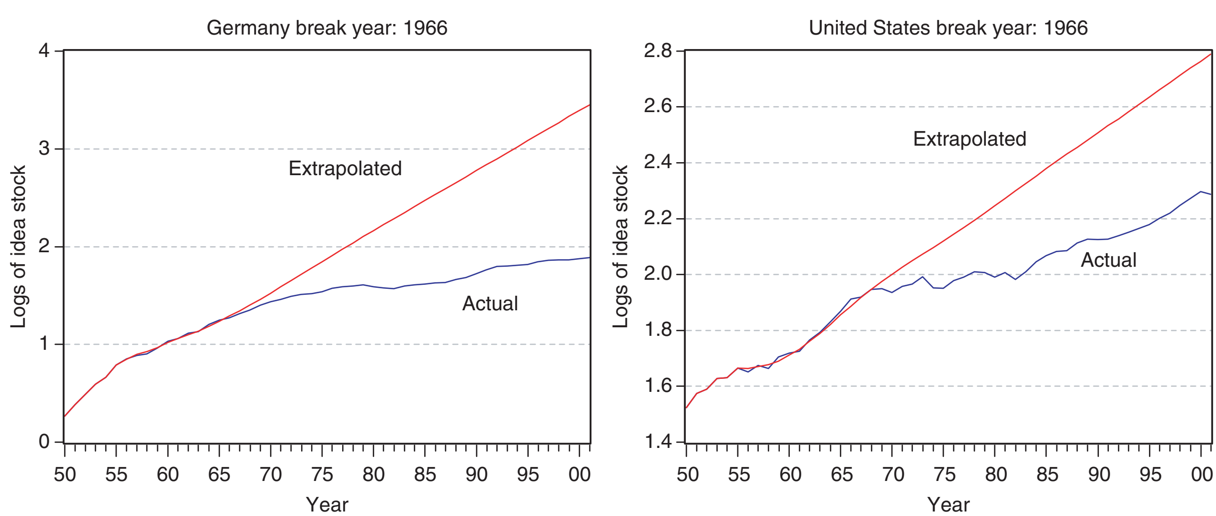

Fig. 2. Slowdown in idea stock: 1950–2001. Trend break years are above the panels. No breaks are detected in the series of ideas for France and the United Kingdom. The scales of the panels are not the same

Table 3. Pre- and post-break steady states

Coefficients	USA		GER		FRA		UK	
(A) Researchers and scientists								
β	0.014		0.027		0.019		0.009	
γ_1	−0.006		−0.012		−0.011		−0.006	
γ_2			−0.011					
$\Delta y_{1,t<TB}$	0.056	(10.86)	0.073	(13.89)	0.067	(17.18)	0.048	(6.85)
$\Delta y_{2,t>TB}$	0.031	(29.34)	0.010	(1.43)	0.030	(8.02)	0.014	(5.84)
$\Delta y_2 - \Delta y_1$	−0.025		−0.063		−0.038		−0.034	
$\Delta y_2/\Delta y_1$	0.56		0.14		0.44		0.29	
(B) Idea stock								
β	0.008		0.013					
γ_1	−0.003		−0.009					
$\Delta y_{1,t<TB}$	0.022	(11.76)	0.062	(8.31)				
$\Delta y_{2,t>TB}$	0.014	(12.87)	0.016	(4.43)				
$\Delta y_2 - \Delta y_1$	−0.008		−0.046					
$\Delta y_2/\Delta y_1$	0.64		0.25					

Notes: The asymptotic *t*-statistics are in parentheses; those of Δy_1 and Δy_2, calculated using the delta method, are in parentheses. No trend breaks are detected in the series of ideas for France and the United Kingdom. The most likely trend breakpoints for idea stock in both countries are 1966 and 1973, respectively.

Assuming that the use of this framework keeps on offering evidence against the unit root null hypothesis, we provide additional information in order to reinforce the validity of these assumptions. Therefore, we present and use (in Appendix C) the Bai and Perron (1998, 2003a, 2003b) methodology as worthy complement in order to study the presence of breaks in the trend. A key feature of this procedure is that it allows testing for multiple breaks at unknown dates, so that it successfully estimates each break point by using a specific-to-general strategy in order to determine the number of breaks consistently. In that respect, it is of interest to highlight that the results reported in the main body of the text are not modified in any way by the application of this new set of statistics.

[While we mentioned earlier that the tests do no reject the hypothesis of a nonintegrated process, this could be elaborated upon further. The number of scientists and engineers obviously cannot keep growing forever at a constant rate. So saturation would suggest a nonintegrative hypothesis, such as a logistic without trend breaks. We will test for this alternative on United States research intensity, as stated in Appendix D.]

Now that the reach and nature of the breaks have been seen, the (actual) rate of growth along the path of the steady state is compared with what it would have been (counterfactual), if the original path had not been interrupted by the structural change. Steady state growth rates were calculated from Equations 6 and 7 using the estimated coefficients for the trend ($\hat{\beta}$) and lagged $y(\hat{c}_j s)$. The post-break growth rates also incorporate the coefficient for the trend dummy variable ($\hat{\gamma}$). One of the main implications of the estimates is that the average rates of growth after the break of the 1960s depress the previous growth rates. Before that period, researchers and scientists hardly ever grew below a level of 5% (Table 3, panel A). Afterwards, only the United States and France grow at 3%, while in Germany and the United Kingdom they scarcely rise beyond 1%. As a consequence, the difference between average growth rates of the steady states is $\Delta y_2 - \Delta y_1 = -0.04$. In parallel fashion, the ratios of second period to first period $\Delta y_2/\Delta y_1$ range from 0.56 in the United States to 0.14 in Germany.

The unequal intensity of the crisis in these two countries is reproduced in relation to the ideas (Table 3, panel B). The difference between the growth rates of the final and initial steady states, which is of −0.8% points in the United States, reaches −4.6 points in Germany (ratios of 0.64 and 0.25, respectively). Perhaps the most striking aspect of the process is that, after the structural change, new ideas grow almost at the same rhythm (1.4% and 1.6%) in both countries. In France and Great Britain, meanwhile, there is no evidence of breaks in the growth path.

The four countries exhibit features which evidence that both researchers and ideas moved onto a lower growth path after the break in the 1960s. To what point did the trends continue to descend afterwards? An intuitive approach consists in comparing their growth rates between 1950 and the first break year (T_{B1}) with the average between the last rupture (T_{Bm}) and 2001. The steady state growth rates were calculated for the baseline period and also for the final one in each country and reported in Table 4.

Table 4. Growth rate comparison of steady states

	USA	GER	FRA	UK
(A) Researchers and scientists				
Break year (T_B)	1967	1963 1989	1966	1968
Pre-T_{B1} (a)	7.4	8.0	7.3	6.3
Post-T_{Bm} (b)	2.6	3.4	3.6	2.7
Ratio ($c = b/a$)	0.35	0.43	0.49	0.42
(B) Idea stock				
Break year (i)	1966	1966		
Pre-T_{B1} (a)	2.4	6.3		
Post-T_{Bm} (b)	1.1	1.8		
Ratio ($c = b/a$)	0.44	0.28		

Notes: Average annual rates, in percentages. No trend breaks are detected in the series of ideas for France and the United Kingdom.

The last row provides an indication of the extent of the deceleration. As a general rule, the average annual growth rates of the final path were around 40% of those registered in the base path. The figures, along with the synchrony of the changes, reinforce the thesis of a strong correlation between processes of research intensity and discovery of new ideas in the United States. It is not sufficiently clear whether this occurs in the case of the European countries.

The consequences of the changes in structure are of significance, bearing in mind the relationship between research, technical progress and growth. In the United States, at the rate of balanced growth prior to the break of 1967, the number of researchers and scientists doubled approximately every 14 years. Afterwards, the time required to do this had risen to over 23 years. What are the effects of the slowdown on the rhythms of advance of new ideas? From Jones (2002) and the observation of the difference between the initial and final steady states, the ceteris paribus TFP would have managed to increase to a rate of 2.16% between 1976 and 2001; that is 58% more than the 1.37% actually registered. In the case of Germany, the potential increase is far more substantial, because there is a difference of 4.6% points, above the meagre 1.57% achieved.

Did these countries depart from the original steady state path? The answer appears to be affirmative, although a wider-reaching perspective would be required to respond to the question. Let us take a look at the researcher series: the ratio between growth rates after the last break and prior to the first scarcely surpasses a share of 0.50 on average. If, maintaining the numerator, the growth rate for the period between the first and second breaks is calculated on the denominator, the ratio is around 0.75–0.80. In other words, it has nowhere near recovered the post-trend break standards of the 1960s. From a long-term perspective, such a supposition is far from clear.

Still, with the main focus on the trend breaks in R&D process, to what degree are we dealing with definitive changes? The neoclassical model foresees a dynamic of transitory deviations from the balanced growth path. In the degree to which the vigorous growth observed up to the second half of the 1960s reflects a transitional period, it could not possibly be sustained indefinitely. But our results also seem compatible with the fact that technological diffusion becomes increasingly difficult as the lagging countries draw closer to the frontier represented by the leader.

V. Concluding Remarks

Our study sets out to characterise possible breaks in the R&D process in the United States and Europe, in the second half of the 20th century. Several caveats need to be emphasised. First, the growth rate of TFP in the OECD countries has declined over the past decades, while the shares of GDP devoted to R&D simultaneously show signs of stagnating. Second, the countries experience a trend and level break in the researcher series for the mid-1960s, with a slight variation in break-year dates. The results as a whole also corroborate the thesis of new ideas slowdown, in the middle of the 1960s (coinciding, moreover, in the United States with the first oil crisis).

Third, the pre-break rates are higher than their post-break equivalents. In this connection, the United States and Germany appear to represent the end points in the range of incidence. In the former country, the slowdown involves a reduction in research growth rate, from 5.6% until 1967, later dropping to 3.1%. In Germany, the fall is far more dramatic, because it drops from 7.3% before 1963 to a mere 1% after that date. Parallel to these situations, the break in the idea stock growth path in 1966 meant that TFP was reduced by a third in the United States and by three quarters in Germany. Finally, the synchrony between researchers and ideas growth processes, in the United States, reinforces the thesis of mutual interaction between them. Meanwhile correlation seems not to be as close among the European countries as it does in the United States.

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References

Andrews, D. W. K. (1991) Heteroskedasticity and autocorrelation consistent covariance matrix estimation, *Econometrica*, **59**, 817–58.

Andrews, D. W. K. (1993) Tests for parameter instability and structural change with unknown change point, *Econometrica*, **61**, 821–56.

Andrews, D. W. K. and Monahan, J. C. (1992) An improved heteroskedasticity and autocorrelation consistent covariance matrix estimator, *Econometrica*, **60**, 953–66.

Andrews, D. W. K. and Ploberger, W. (1994) Optimal tests when a nuisance parameter is present only under the alternative, *Econometrica*, **62**, 1383–414.

Andrews, D. W. K., Lee, I. and Ploberger, W. (1996) Optimal changepoint tests for normal lineal regression, *Econometrica*, **64**, 9–38.

Atella, V. and Quintieri, B. (2001) Do R&D expenditures really matter for TFP?, *Applied Economics*, **33**, 1385–9.

Atkins, F. J. and Chan, M. (2004) Trend breaks and the fisher hypothesis in canada and the united states, *Applied Economics*, **36**, 1907–13.

Bai, J. and Perron, P. (1998) Estimating and testing linear models with multiple structural changes, *Econometrica*, **66**, 47–78.

Bai, J. and Perron, P. (2003a) Computation and analysis of multiple structural change models, *Journal of Applied Econometrics*, **18**, 1–22.

Bai, J. and Perron, P. (2003b) Critical values for multiple structural change tests, *Econometrics Journal*, **6**, 75–8.

Banerjee, A., Lumsdaine, R. L. and Stock, J. H. (1992) Recursive and sequential tests for a unit root: theory and international evidence, *Journal of Business and Economic Statistics*, **10**, 271–87.

Ben-David, D. and Papell, D. H. (1995) The great wars, the great crash and the unit root hypothesis: some new evidence about an old stylised fact, *Journal of Monetary Economics*, **36**, 453–75.

Ben-David, D. and Papell, D. H. (1998) Slowdowns and meltdowns: postwar evidence from 74 countries, *Review of Economics and Statistics*, **80**, 561–71.

Ben-David, D. and Papell, D. H. (2000) Some evidence on the continuity of the growth process among the G7 countries, *Economic Inquiry*, **2**, 320–30.

Ben-David, D., Lumsdaine, R. L. and Papell, D. H. (2003) Unit roots, postwar slowdowns and long run growth: evidence from two structural breaks, *Empirical Economics*, **28**, 303–19.

Bils, M. and Klenow, P. J. (2000) Does schooling cause growth?, *American Economic Review*, **90**, 1160–83.

Brown, R. L., Durbin, J. and Evans, J. M. (1975) Techniques for testing the constancy of regression relationships over time, *Journal of Royal Statistical Society Series B*, **37**, 149–63.

Campbell, J. Y. and Perron, P. (1991) Pitfalls and opportunities: what macroeconomists should know about unit roots, *NBER Macroeconomics Annual*, **6**, 141–201.

Chow, G. C. (1960) Tests for inequality between sets of coefficients in two linear regressions, *Econometrica*, **28**, 591–605.

De la Fuente, A. and Doménech, R. (2002) Human capital in growth regressions: how much difference does data quality make?, *Journal of the European Economic Association*, **4**, 1–36.

Griliches, Z. (1990) Patent statistics and economic indicators: a survey, *Journal of Economic Literature*, **18**, 1661–707.

Griliches, Z. (1994) Productivity, R&D and the data constraint, *American Economic Review*, **84**, 1–23.

Harberger, A. and Wisecarver, D. (1977) Private and social rates of return to capital in Uruguay, *Economic Development and Cultural Change*, **25**, 411–45.

Harvey, D. I. and Mills, T. C. (2005) Evidence for common features in G7 macroeconomic time series, *Applied Economics*, **37**, 165–75.

Jiménez-Rodríguez, R. and Sánchez, M. (2005) Oil price shocks and real GDP growth: empirical evidence for some OECD countries, *Applied Economics*, **37**, 201–28.

Jones, Ch. I. (1995) R&D based models of economic growth, *Journal of Political Economy*, **103**, 759–84.

Jones, Ch. I. (2002) Sources of US economic growth in a world of ideas, *American Economic Review*, **92**, 220–39.

Layton, A. P. and Banerdji, A. (2003) What is a recession?: a reprise, *Applied Economics*, **35**, 1789–97.

Liu, J., Wu, S. and Zideck, J. V. (1997) On segmented multivariate regressions, *Statistica Sinica*, **7**, 497–525.

Lumsdaine, L. R. and Papell, D. H. (1997) Multiple trend breaks and the unit root hypothesis, *Review of Economics and Statistics*, **79**, 212–8.

Keely, L. C. and Quah, D. (1998) Technology in growth. Centre for Economic Performance, Discussion Paper No. 391.

Maddison, A. (1995a) *Explaining the Economic Performance of Nations: Essays in Time and Space*. *Economists of the Twentieth Century Series*, Edward Elgar, Aldershot, Hants.

Maddison, A. (1995b) *Monitoring the World Economy, 1820–1992*, Organisation for Economic Cooperation and Development, Paris.

Perron, P. (1989) The great crash, the oil price shock and the unit-root hypothesis, *Econometrica*, **57**, 1361–401.

Perron, P. (1997) Further evidence on breaking trend functions in macroeconomic variables, *Journal of Econometrics*, **80**, 355–85.

Romer, P. M. (1990) Endogenous technological change, *Journal of Political Economy*, **98**, 71–102.

Romer, P. M. (2000) Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?, NBER Working Paper No. 7723.

Sen, A. (2004) Are US macroeconomic series difference stationary or trend-break stationary?, *Applied Economics*, **36**, 2025–9.

Verspagen, B. (1996) Technology indicators and economic growth, *Quantitative Aspects of Post-War European Growth*, Cambridge University Press, Cambridge, pp. 215–43.
Vogelsang, T. J. and Perron, P. (1998) Additional tests for a unit-root allowing for a break in the trend function at a unknown time, *International Economic Review*, **39**, 1073–100.
Yao, Y. C. (1988) Estimating the number of change-points via schwarz's criterion, *Statistics and Probability Letters*, **6**, 181–9.
Zivot, E. and Andrews, D. W. K. (1992) Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis, *Journal of Business and Economic Statistics*, **10**, 251–70.

Appendix A: Data Sources

- *GDP per Hour*. The data for GDP at 1990's constant prices were calculated using Eurostat (Statistical appendix to European Economy). The values corresponding to the period 1950 to 1960 are based on the GDP Movement series provided by Maddison (1995a). Weekly working hours in nonagricultural activities were obtained from the Work Statistics Directories, published by the International Labour Organization (ILO), whilst it was necessary to use various issues of the OECD Labour Force Statistics in order to estimate some of the values for the United Kingdom.
- *Human Capital*. The data for average years of educational training for population over 25 years old come from De la Fuente and Doménech (2006) (updated to 2003).
- *Engineers and Scientists Engaged in R&D activities*. The source (National Science Board and OECD) is the same as in Jones (2002). The figures for Germany until 1989 are the sum of the old Federal and Democratic Republics. For the years prior to 1960, it was assumed that the ratio of 'research intensity' for the three European countries in relation to the United States was the same in 1950 as in 1960. This ratio was interpolated for the intermediate years and then multiplied by employment.
- *People in work*. The starting point is the total employment in 1960, obtained from OECD Labour Force Statistics. The series for the following years was obtained by applying to that number the rates of variation provided by Eurostat, in European Economy. In contrast, the series for the preceding years, 1950–1960, is the result of deducting the annual variations provided by Maddison (1995b) from the number of people employed in 1960.
- *R&D expenditures*. OECD, Main Science and Technology Indicators (various years) and Verspagen (1996) for dates prior to 1990.

Appendix B: Trend Break Tests

Table B1. Trend break tests results: researchers

	USA		GER		FRA		UK	
Trend breaks								
T_{B1}	1967		1989		1966		1968	
T_{B2}			1963		1980			
Coefficients								
$\hat{\mu}$	1.321	(6.80)	1.138	(5.12)	0.793	(4.65)	0.662	(4.81)
$\hat{\theta}_1$	−0.049	(4.24)	0.080	(3.43)			0.048	(3.36)
$\hat{\theta}_2$					0.055	(3.79)		
$\hat{\beta}$	0.014	(4.33)	0.027	(4.10)	0.019	(3.80)	0.009	(3.07)
$\hat{\gamma}_1$	−0.006	(2.73)	−0.012	(4.02)	−0.011	(4.32)	−0.006	(2.88)
$\hat{\gamma}_2$			−0.011	(3.04)				
$\hat{c}_1$	1.17[a]		1.02[a]		0.92[a]		1.11[a]	
$\hat{c}_2$	−0.35[c]		−0.39[b]		−0.29		−0.30[b]	
$\hat{c}_3$	0.19				0.35[c]			
$\hat{c}_4$	−0.35[c]				−0.27[b]			
$\hat{c}_5$	0.32[b]							
$\hat{c}_6$	−0.24[b]							

Notes: The asymptotic *t*-statistics are in parentheses. The letters [a],[b] and [c] denote statistical significance at the 1, 5 and 10% levels, respectively.

Table B2. Trend break tests results: idea stock

	USA		GER		UK	
Trend breaks						
T_{B1}	1966		1966		1962	
T_{B2}	1973					
Coefficients						
$\hat{\mu}$	0.553	(4.21)	0.068	(1.99)	0.191	(3.00)
$\hat{\theta}_1$					0.032	(3.08)
$\hat{\theta}_2$	−0.034	(3.48)				
$\hat{\beta}$	0.008	(3.63)	0.013	(3.55)	0.002	(2.30)
$\hat{\gamma}_1$	−0.003	(2.27)	−0.009	(3.46)		
$\hat{c}_1$	0.64[a]		0.98[a]		0.79[a]	
$\hat{c}_2$			−0.10			
$\hat{c}_3$			−0.22			
$\hat{c}_4$			0.24			
$\hat{c}_5$			0.16			
$\hat{c}_6$			−0.27[b]			

Notes: The asymptotic *t*-statistics are in parentheses. The letters [a] and [b] denote statistical significance at the 1 and 5 levels, respectively.

Appendix C: Testing for Multiple Structural Breaks

Earlier work by, e.g. Chow (1960) or Brown *et al.* (1975), focused on testing for structural change at a single known break data. More recently, however, the econometric literature has developed methods that allow estimating and testing for structural change at unknown break dates; see Andrews (1993) and Andrews and Ploberger (1994) for the case of a single structural change and Andrews *et al.* (1996), Liu *et al.* (1997) and Bai and Perron (1998, 2003a, 2003b) for the case of multiple structural changes.

A key feature of the Bai and Perron procedure is that it allows testing for multiple breaks at 'unknown' dates, so that each break point is successively estimated by using a specific-to-general strategy in order to determine consistently the number of breaks. As an additional advantage, the Bai and Perron procedure allows investigating whether some or all the parameters of the estimated relationship have changed.

More specifically, Bai and Perron (1998, 2003a) consider a linear model with m multiple structural changes (i.e. $m+1$ regimes), such as:

$$y_t = z_t'\delta_1 + u_t, \quad t = 1, \dots, T_1,$$
$$y_t = z_t'\delta_2 + u_t, \quad t = T_1 + 1, \dots, T_2,$$
$$\dots$$
$$y_t = z_t'\delta_{m+1} + u_t, \quad t = T_m + 1, \dots, T$$

where y_t is the observed dependent variable at time t, $Z_t(q \times 1)$ is a matrix of regressors, $\delta_j\,(j = 1, \dots, m+1)$ is the corresponding vector of coefficients and u_t is the error term at time t. The indices $\{\bar{z}\}$, i.e. the break points, are explicitly treated as unknown.

The issue of testing for structural changes is also considered under very general conditions on the data and the errors. The Bai and Perron tests are based upon an information criterion in the context of a sequential procedure and allows one to find the numbers of breaks implied by the data, as well as estimating the timing and the confidence intervals of the breaks and the parameters of the processes between breaks. This procedure, on the other hand, is not computationally excessive, allowing for the computation of the estimates using at most least-squares operations of order $O(T^2)$ for any number of structural changes m, unlike a standard grid search procedure which would require least squares operation of order $O(T^m)$.

Bai and Perron (1998, 2003a) propose three methods to determine the number of breaks: a sequential procedure, SP (Bai and Perron, 1998); the Schwarz modified criterion, LWZ (Liu *et al.*, 1997); and the Bayesian information criterion, BIC (Yao, 1988). Finally, the authors suggest several statistics in order to identify the break points:

- The $\sup F_T(k)$ test, i.e. a $\sup F$-type test of the null hypothesis of no structural break ($m = 0$) vs. the alternative of a fixed (arbitrary) number of breaks ($m = k$).
- Two maximum tests of the null hypothesis of no structural break ($m = 0$) vs. the alternative of a unknown number of breaks given some upper bound M ($1 \le m \le M$), i.e. *UD* max test, an equal weighted version and *WD* max test, with weights that depend on the number of regressors and the significance level of the test.
- The $\sup F_T(l+1|l)$ test, i.e., a sequential test of the null hypothesis of l breaks vs. the alternative of $l+1$ breaks.

The results of using the tests are shown in Table C1. We have applied the Bai and Perron procedures with a constant, a trend and one lag of dependent variable as regressor, allowing up to 3 breaks and constraining each segment to have at least 10 observations. The $\sup F_T(k)$ tests are significant for all series. The *UD* max and *WD* max are also highly significant. So, at least one break is present. In the case of the researcher and scientist series the sequential procedure (using a 5% significance level) selects two breaks for Germany and France and one break for the US and Great Britain.

Table C1. Tests for multiple structural breaks in lineal models: the Bai and Perron procedure

Test	USA[f]	GER[f]	FRA[f]	UK[f]
(A) Researchers and scientists				
Sup $F_T(1)$[a,c,e]	34.55***	13.97**	23.62***	18.25***
Sup $F_T(2)$[a,c,e]	26.27***	12.68***	24.55***	23.20***
Sup $F_T(3)$[a,c,e]	21.29***	17.88***	19.44***	15.97***
UD max	34.45***	17.88***	24.55***	23.20***
WD max	34.4***	29.80***	32.42***	30.63***
Sup $F_T(2\|1)$[c,e]	13.93**	20.83***	14.13**	15.53***
Sup $F_T(3\|2)$[c,e]	10.70	22.86***	6.56	2.54
l[b]	1	2	2	1
$\hat{T}_1^d$	1966	1965	1964	1967
$\hat{T}_2^d$	–	1988	1979	–
$\hat{T}_3^d$	–	–	–	–
(B) Idea stock				
Test	USA[g]	GER[f]	UK[f]	
Sup $F_T(1)$[a,c,e]	19.05***	19.30***	11.62***	
Sup $F_T(2)$[a,c,e]	18.18***	16.92***	8.91*	
Sup $F_T(3)$[a,c,e]	12.62***	11.12***	8.01**	
UD max	19.05***	19.30***	11.62**	
WD max	23.89***	22.34***	12.33**	
Sup $F_T(2\|1)$[c,e]	16.08**	8.00	6.35	
Sup $F_T(3\|2)$[c,e]	4.72	1.51	3.86	
l[b]	2	1	1	
$\hat{T}_1^d$	1960	1986	1961	
$\hat{T}_2^d$	1972	–	–	
$\hat{T}_3^d$	–	–	–	

Notes: [a]The sup $F_T(k)$ tests and the confidence intervals allow for the possibility of serial correlation in the disturbances. The heteroskedasticity and the autocorrelation consistent covariance matrix is constructed following Andrews (1991) and Andrews and Monahan (1992) using a quadratic kernel with automatic bandwidth selection based on an AR(1) approximation. The residuals are pre-whitened using a VAR(1).
[b]l is the number of breaks obtained from the sequential procedure (SP) at the 5% size for the sequential test sup $F_T(l+1|l)$.
[c]In the implementation of the procedure, we allowed up to three breaks ($M=3$) and we use a trimming $\varepsilon=0.20$ which corresponds to each segment having at least 10 observations.
[d]$T_{i=1,2}$ are the break dates estimated.
[e]A*, ** and *** denote significance at the 10, 5 and 1% levels, respectively.
[f]We apply the procedure with the dependent variable, y_t, a constant and one lag of y_t as regressor $[z_t=\{1, y_{t-1}\}]$.
[g]We apply the procedure with the dependent variable, y_t, a constant, a trend and one lag of y_t as regressor $[z_t=\{1, t, y_{t-1}\}]$.

In the case of the idea stock series the sequential procedure (using a 5% significance level) selects two breaks in US and one break for Germany and Great Britain; no breaks are detected in the series of ideas for France.

Thus, the Bai and Perron procedure depicts trend breaks that fit properly the shifts provided above in the text, both in the researcher and in the idea stock series, except for one. It detects indeed a trend break in German idea stock in 1986 out of keeping with the Perron (1997) and Ben-David and Papell (2000) procedures. However it is worthy of attention to highlight that the later point to a likely level break that year. Therefore, the new estimates reinforce as a whole the results we get in Table 2. The conclusion reached again is that there are structural breaks in the series around the mid-sixties. Nonetheless, we recognise that the GLS tests present better properties (size and power) than those of OLS tests.

Appendix D: Testing for a Logistic Alternative

The logistic curve is given by the equation:

$$l_A = \frac{l_{Amax}}{1 + be^{-cT}}$$

Table D1. Time series estimates of research intensity in US

Coefficients	1950–2001		1950–1967		1967–1973		1973–2001	
$\log b$	1.16	(75.60)	1.30	(132.08)	0.68	(51.66)	1.22	(89.69)
c	−0.006	(11.45)	−0.021	(23.09)	0.015	(23.73)	−0.007	(19.65)
R^2	0.72		0.97		0.99		0.93	
SE	0.055		0.020		0.003		0.016	
Sum of squares	0.150		0.006		0.000		0.007	

Note: Newey–West robust t-statistics are in parentheses.

where l_A is research intensity (which to a significant extent consists of the share of researchers in the labour population), l_{Amax} is the (known) saturation level and T is the number of observations. The above equation is an S-shaped curve, which may be used to represent the research intensity that ceteris paribus will someday saturate the market. Now, by taking the natural logarithm of both sides and rearranging terms, this leads to:

$$\log\left(\frac{l_{Amax}}{l_{At}} - 1\right) = \log b - cT_t + \varepsilon_t$$

where the disturbance term ε_t is assumed to be serially uncorrelated and orthogonal to the explanatory variables. The share of the population that works in research is obtained by setting $l_A = L_A/L$. Suppose the stocks K and A growth at constant rates. In this case, substituting for $l_Y = 1 - l_A$ in Equation 10 from Jones (2002), output per worker $y_t = Y_t/L_t$ can be decomposed as:

$$y_t^* = \left(\frac{s_{Kt}^*}{n + g_k + d}\right)^{\alpha/1-\alpha}(1 - l_{At})h_t\left(\frac{\delta}{g_A}\right)^{\gamma/\lambda}(l_{At}L_t^*)^{\gamma}$$

where $k \equiv K/L$ and $\gamma \equiv (\sigma/1-\alpha)(\lambda/1-\phi)$. Notice that $l_A L$ is just H_A. Here, g_x represents the constant growth rate of some variable x and an asterisk denotes a quantity that is growing at a constant rate. To maximize output per worker along a balanced growth path, take the derivative respect to l_A:

$$\frac{\partial y^*(t)}{\partial l_A} = B\frac{\partial(1 - l_A)l_A^{\gamma}}{\partial l_A}$$

where

$$B = \left(\frac{s_{Kt}^*}{n + g_k + d}\right)^{(\alpha/1-\alpha)} h_t\left(\frac{\delta}{g_A}\right)^{(\gamma/\lambda)} L_t^{*\gamma}$$

The maximum occurs when the derivative is equal to zero and $(\partial y^*(t)/\partial l_A) = 0$ implies that

$$l_A^*\left[1 - (1 - l_A^*)\gamma\frac{1}{l_A^*}\right] = 0$$

Solving the equation for l_A^* then (in addition to the trite $l_A^* = 0$) reveals:

$$l_A^* = \frac{\gamma}{1 + \gamma}$$

Jones (2002) restricted estimates of γ for the US between 1950 and 1993 range from 0.178 when $\lambda = 1$ to 0.076 when $\lambda = 0.25$, with an intermediate value of $\gamma = 0.123$. With this parameter value, we have $l_A^* = 0.109$.

Table D1 reports estimates from upper regressions for USA, setting $l_{Amax} = l_A^*$. They are a mixture of good news and bad news. Looking at the good news first, we see that the specification appears to be statistically sensitive to the different sample periods. Both coefficients are well determined by conventional standards. Now look at the bad news. The earlier 1950 to 1967 and the later 1973 to 2001 periods yield c coefficients of the same (negative) sign, while the estimate for the intermediate 1967 to 1973 period changes to a positive one. The hypothesis of stability is decisively rejected for the Chow test, the F-statistic registering at 233.1, which far exceeds any standard critical value. The tabled critical value (1% significance) is 5.10, so, consistent with our expectations, we reject the hypothesis that the coefficient vectors are the same in the three periods.