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International Differences in R&D: An Empirical Investigation of a 'Quality Ladder' Implication

WERNER ANTWEILER JR.*

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Abstract

R&D varies substantially across countries. By introducing the profit motive into R&D, the "quality ladder" growth model implies an inverse relationship between the national activity levels of R&D and unit costs of R&D. This inverse relationship is supported by findings from a data set of direct measures and a second data set that contains measures based on the R&D content of international trade.

JEL Classification: F12, O41.
Keywords: International R&D Competition; R&D Content of Trade

1 Introduction

The accumulation of knowledge through Research and Development (R&D) is a key factor in the growth of nations. New approaches have emphasized the microeconomic profit incentives for conducting R&D. In particular, Grossman and Helpman (1989, 1990, 1991a-c) and Feenstra (1990) have developed an imperfectly competitive "quality ladder" model that captures this profit incentive through a no-arbitrage condition relating a country's R&D unit costs to its R&D level and that of its competitors. With imperfect competition, domestic R&D decisions impose negative externalities that reduce foreign competitors' incentives to conduct R&D. While externalities typically play havoc with empirical work, I provide conditions under which empirical implementation of the Grossman and Helpman no-arbitrage condition is tractable. In particular, I show that their no-arbitrage condition is supported by the data. I avoid the use of the stronger "testing" terminology because no alternative hypothesis is specified.

The basic insight can be expressed by the "quality ladder" model of endogenous technological growth presented below. With monopolistic competition, rates of return on R&D investments

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(i.e., equity positions in firms developing innovative products) must be equated. Thus, if a firm has low development costs, then it must be facing competitors with high success rates of product development; otherwise, the firm would be earning abnormally high rates of return. This logic implies an inverse relationship between development costs (i.e., the unit costs of the R&D input) and rates of innovation by competitors (i.e, the output of the R&D process or what Grossman and Helpman call "research intensity").

There are two key issues with the empirical implementation of the model. The first deals with why R&D unit costs vary across countries. In the absence of such variation there should be no relationship between R&D unit costs and research intensities. I appeal to several sources of variation including national policies that put a wedge between private and social R&D costs, the existence of non-tradeable goods that use R&D as an input, and the possibility that factor prices are not equalized. The second issue is that the relationship to be examined involves impossibly detailed information on each firm's costs and research intensities of its international competitors. I derive two conditions under which this information can be backed out of available data sources: the distribution of innovation leadership across countries is in steady state and countries' average size of R&D-using firms is the same. The available data are international differences in R&D as reported in the OECD (1992) Main Science and Technology Indicators data set and a factor content calculation of international trade in R&D services. The latter is related to the Helpman (1984) factor endowments model without factor price equalization. Coe and Helpman (1993) have used the same OECD data to investigate R&D productivity and international R&D spillovers.

The conclusion that derives from both data sources is that *countries' R&D unit costs are inversely related to research intensity as predicted by the Grossman and Helpman no-arbitrage condition*. This suggests that microeconomic incentives for conducting R&D are key to understanding international differences in growth performance. More generally, I document and indicate the significance of cross-country and cross-industry differences in R&D.

2 The "Quality Ladder" Approach to Economic Growth

Microeconomic incentives for R&D are based on technological leadership. The new growth literature points at a variety of reasons for such leadership: firms can invent new products in a world of ever-increasing product variety, or they can improve the quality of existing goods, or they can engage in an invention-imitation race.[1]

The "quality ladder" model explores the quality dimension of goods. Product quality follows a stochastic progression in discrete and constant steps of size $\lambda > 1$ up a "quality ladder" (i.e., a quality index).[2] Consumers prefer goods that are qualitatively superior (i.e., cheaper in terms of their quality-adjusted price), so that innovators compete in advancing the quality of products. By improving a good an entrepreneur gains a competitive edge in a market. The resulting temporary monopoly ensures that innovators can recoup their R&D costs.

Infinitely-lived consumers in the "quality ladder" model maximize utility intertemporally so that in a two-stage budgeting process expenditures are first allocated over time and then over goods. As in Taylor (1993), the model can be easily extended to incorporate homothetic consumer preferences that are standard in the Heckscher-Ohlin set-up. Households consume a quantity $q_{k,m}$

[1] See, for example, Stokey (1991) and Segerstrom (1991).

[2] Taylor (1993) analyzes the consequences of step size variations.

of good k of generation m and pay a price $p_{k,m}$, amounting to an expenditure $s_k E$. A share of $\sum_{k=1}^{n} s_k = \sigma < 1$ is alotted to n quality improving goods, and the remaining share of $(1-\sigma)$ to goods whose quality remains constant. The corresponding maximization problem shows (see Grossman/Helpman 1991c) that total expenditure growth $\dot{E}/E$ equals the instantaneous real interest rate (r) minus the personal discount rate (ρ):

$$\dot{E}/E = r - \rho. \tag{1}$$

The "quality ladder" model assumes a particular form of interindustry, intertemporal, and intraindustry technological spillovers.[3] Technological spillovers are limited to each market so that a firm does not benefit from innovations in other markets. If a firm fails to innovate first, then any technical advances are lost as inputs into subsequent research. On the other hand, once a firm succeeds with an innovation, competitors are able to re-engineer this innovation and incorporate the new technology into their efforts to improve upon the current innovation level. With each innovation, the new technology becomes public knowledge, but the innovator's lead is protected by, for example, patents. This means that success does not breed future success, nor is failure a recipe for poor future performance.

Consider a firm i operating in market k. With factor wages w, firm i's unit production costs are $c_{i,k}(w)$ for good k and $c_{i,\iota}(w)$ for R&D. Firms engage in Bertrand price competition. This implies that an innovating firm under-prices its lower quality rivals and drives them from the market. Consequently, an innovator who captures a market will be able to make profits. Since consumers choose the lowest quality-adjusted price, the pricing rule states that the price of a good that is Δm generations ahead is $p_k = \lambda^{\Delta m} c_{i,k}(w)$. If a producer were to charge more than $\lambda^{\Delta m} w$, a good of lower quality would be more cost-efficient for the consumers. Quality leaders will only be one generation ahead.[4] Thus in equilibrium the firm captures the entire market, and profits are $\pi_i = [p_k - c_{i,k}(w)]q_k$. Quantities q_k are equal to $s_k E/p_k$ for the quality leader and zero for the other firms. Hence firm i that leads in market $k = i$ earns profits

$$\pi_i(\lambda) = \left(1 - \frac{1}{\lambda}\right) s_i E \tag{2}$$

while its rivals who are driven from market earn zero profits.

The stock market value of a quality leader is ν_i. Since there is free entry into the R&D industry, competition eliminates profits and the stock market value must equal the production cost of a single innovation $c_{i,\iota}(w)$. Equity holders obtain a dividend stream $\pi_i(\lambda)$ and realize capital gains $\dot{\nu}_i$ when firm i retains its leadership.

Investors arbitrage equates returns on investments in R&D and other assets. R&D investments yield a return that equals the ratio of expected profits to equity, and other assets yield a return that equals r. Let ι_i be the research intensity directed at firm i and $\iota_i dt$ the probability of an innovation success in time interval dt. With probability $(1-\iota_i dt)$ firm i remains the market leader with profits equal to the dividend stream plus capital gains; with probability $(\iota_i dt)$ firm i is driven from the

[3] See Grossman and Helpman (1991c, p. 48) and Grossman and Helpman (1991a, p. 85, 92–94) for a justification of the following assumptions.

[4] Grossman and Helpman (1991c, p. 46) prove this for the case of identical budget shares s_k for all goods. With homothetic preferences it is possible that $s_k \neq s_j$. Then the condition that ensures that no firm is leading more than one generation is $\lambda > s_k/s_j$.

market and investors lose their equity. That is,

$$(1-\iota_i dt)[\pi_i(\lambda)dt + \dot{\nu}_i dt] + (\iota_i dt)[-\nu_i] = r\nu_i dt. \tag{3}$$

In a steady state expenditure growth will be zero ($\dot{E}=0$); thus equation (1) implies $r=\rho$. Moreover, there will be no capital gains ($\dot{\nu}_i = 0$). Since profits $\pi_i(\lambda)$ grow with market size, this sensibly implies that a small industry faces a lower R&D intensity than a big industry. Using the free entry condition $\nu_i = c_{i,\iota}(w)$, imposing the steady state conditions, and noting that $(1-\iota_i dt) \approx 1$, I obtain

$$\pi_i(\lambda)/c_{i,\iota}(w) = \rho + \iota_i \tag{4}$$

This no-arbitrage condition is the implication I wish to examine. It is central to introducing the profit motive into the study of endogenous growth and might be expected of most profit-maximizing models. In particular, the relationship comes close to implying a negative correlation between research costs and research intensities: holding the dividend stream constant, $c_{i,\iota}(w)$ and ι_i are inversely related.

3 Empirical Implementation: International R&D competition

Empirically investigating the negative correlation between research intensity and unit costs is not straight-forward. For example, ι_i is not observable because it requires data on all the firms' competitors. Significantly, many of the R&D competitors are located abroad so that it is necessary to use international data. This is just a reflection of the globalization of innovative activity.

Consider the no-arbitrage equation (4) for firm i in country c. Putting c subscripts where appropriate and summing over all goods yields

$$\sum_{i=1}^{n_c} \pi_{i,c}(\lambda)/c_{i,c,\iota}(w_c) = \sum_{i=1}^{n_c} (\rho + \iota_{i,c}) \,. \tag{5}$$

Define the average R&D intensity as $\bar{\iota}_c \equiv \sum_{i=1}^{n_c} \iota_{i,c}/n_c$, and define the harmonic mean of R&D unit cost as $\bar{c}_{c,\iota} \equiv \sigma_c / \sum_{i=1}^{n_c}(s_{i,c}/c_{i,c,\iota})$. If innovation unit costs are the same for all firms within a country, i.e. $c_{i,c,\iota} = c_{c,\iota}$, then $\bar{c}_{c,\iota} = c_{c,\iota}$; otherwise $\bar{c}_{c,\iota}$ is a down-biased measure of (weighted) average unit costs. Using equation (2) and the above definitions, equation (5) leads to

$$\left(1-\frac{1}{\lambda}\right)\frac{\sigma_c E_c}{n_c \bar{c}_{c,\iota}(w_c)} = \left(1-\frac{1}{\lambda}\right)\frac{\xi_c}{\bar{c}_{c,\iota}(w_c)} = \rho + \bar{\iota}_c \tag{6}$$

where $\xi_c \equiv \sigma_c E_c / n_c$ is a measure of average firm size in the quality-improving goods sector. Note that ξ_c is proportional to average profits $\sum_{i=1}^{n_c} \pi_{i,c}(\lambda)/n_c$.

I can now formalize the inverse relationship between R&D unit costs and R&D intensity. Following Grossman and Helpman (1991c, p. 57), one can make sensible assumptions about demand elasticities that ensure a negative relationship. However, it greatly simplifies matters to assume that average firm sizes (or average profits) are the same across countries, i.e., $\xi_c = \xi \ \forall c$. This assumption implies empirically that R&D unit costs and R&D intensities explain more of the international variation in equation (6) than internationally diverging average firm sizes. This restriction on ξ_c ensures that the only source of country variation in the no-arbitrage condition (6) is via $\bar{\iota}_c$ and $\bar{c}_{c,\iota}(w_c)$. Without it I would require either knowledge of ξ_c or knowledge of the factor market clearing condition in each country to identify equation (6).

From the perspective of empirical international trade, a key issue in investigating equation (6) is factor price equalization across countries. To see this, suppose that $\bar{c}_{c,\iota}(w_c) = \bar{c}_\iota(w_c)\,\forall c$. With factor price equalization all countries would exhibit equal research intensity. Yet casual preview of the data suggests that research intensities vary substantially across countries, indicating that factor prices vary too. I thus assume that factor prices are not equalized. This also allows me to tie this model to Heckscher-Ohlin trade models without factor price equalization.[5] Such models predict that factor prices and factor contents of trade will be inversely related. I can thus use factor contents as a measure of factor prices, and hence R&D unit costs.

The average research intensity $\bar{\iota}_c$ is still not observable because it is the research intensity *directed at* country c; to measure it requires information about all competitor countries. However, along the lines of Grossman and Helpman (1990, pp. 194-5), in a steady state $\bar{\iota}_c$ is equal to R&D *originating in* country c. To see this, let $\bar{\iota}_{ij}$ denote the research intensity directed by country i against industries in country j, and let $\bar{\iota}_j = \sum_i \bar{\iota}_{ij}$ denote the research intensity directed against country j. Country j leads in n_j industries. In a steady state each country maintains leadership in a constant fraction of the total number of high technology goods so that the inflows balance the outflows: $\bar{\iota}_{ij} n_j = \bar{\iota}_{ji} n_i \ \forall i \neq j$. Then the volume of R&D in country c is the weighted average of the $\bar{\iota}_{cj}$:

$$\sum_j \bar{\iota}_{cj} n_j = \bar{\iota}_{cc} n_c + \sum_{j \neq c} \bar{\iota}_{cj} n_j = \bar{\iota}_{cc} n_c + \sum_{j \neq c} \bar{\iota}_{jc} n_c = n_c \sum_j \bar{\iota}_{jc} = n_c \bar{\iota}_c \tag{7}$$

Hence, country c's steady-state R&D intensity $\bar{\iota}_c$ can be measured solely by *domestic* R&D intensity.

The following theorem collects the empirically-relevant results of this section.

Theorem 1 (International R&D Differences) *For a country c, the inverse of its R&D unit cost $\bar{c}_{c,\iota}(w)$ is a linear function of its own R&D intensity $\bar{\iota}_c$:*

$$[\bar{c}_{c,\iota}(w_c)]^{-1} = \frac{\rho}{\zeta} + \frac{1}{\zeta}\bar{\iota}_c \tag{8}$$

where $\zeta \equiv (1 - 1/\lambda)\xi$.

Note that the theorem is couched entirely in terms of observables and that the functional form follows from the model. Further, it is immediate that there is a negative relationship.

4 Sources of International Variation in R&D

The sources of international variation in equation (8) include differences in prices of R&D inputs w_c and differences in the average cost $\bar{c}_{c,\iota}$. The first source is obvious. I examine the latter two reasons why average costs may differ internationally.

First, countries lead in different sets of goods. Since R&D unit costs will differ across goods, average costs will differ across countries. A common example of different sets of goods is non-tradeables. These may include aerospace products, military goods, and a variety of goods that are location-bound due to internationally diverging system standards (i.e., France's TGV high-speed

[5] See Brecher and Choudhri (1984), Helpman (1984), Deardorff (1982).

trains) and geographical or climatical conditions. Because of the compositional effect, a country with expensive (cheap) R&D of nontradeables will experience a low (high) research intensity.

Second, suppose for argument's sake that both factor prices (w_c) and average R&D unit costs ($\bar{c}_{c,\iota}$) are equalized across countries. If innovators face the same unit costs in each country, research intensities $\bar{\iota}_c$ must equalize too. Otherwise R&D-cheap countries will drive out R&D-expensive countries. Even if social R&D unit costs were equalized across countries, in the presence of country-specific R&D subsidies private R&D unit costs may differ (Grossman and Helpman (1990, p. 264)). Such R&D subsidies could be pecuniary or institutional benefits (e.g., patent lengths, access to government-owned research facilities, government-sponsored training and education programs, and digital communication infrastructure). Formally, let ϕ_c be a subsidy to R&D unit costs so that private unit costs are $(1-\phi_c)\bar{c}_\iota$. Consider two countries A and B. Because of factor price equalization, $\bar{c}_{\iota,A} = \bar{c}_{\iota,B}$. When $\phi_A > \phi_B$, it must hold that $\bar{\iota}_A > \bar{\iota}_B$: countries that subsidize their R&D more will experience lower private R&D unit costs and hence a higher research intensity.

5 Direct Empirical Measures

Equation (8) can be tested directly. Recall that $\alpha \equiv \rho/\zeta$ and $\beta \equiv 1/\zeta$ should show up as positive parameters. Thus the model is *not* supported if (a) β is negative, or (b) β is insignificant, or (c) α/β is strongly negative (indicating a counterfactual high negative real interest rate). While empirical measures of R&D intensity are not too difficult to construct, measures for R&D unit costs are intrinsically hard to approximate. This section suggests three different measures each for R&D intensity and R&D unit costs.

5.1 Measuring the R&D Intensity

I wish to measure the average research intensity, $\bar{\iota}_c$. Ideally, the measure would be an output-based quantity measure that captures the speed of innovation. Such a measure does not exist, forcing me to consider a variety of different features of R&D intensity. Some of these proxies are input rather than output. Some capture only part of the inputs, such as physical or human capital. Others are measured in market values rather than quantities. To improve inter-country comparability, all of the measures group together private and public sector R&D activities. Finally, all of them do not separate innovation speed from innovation size. This may however not be a disadvantage since the quality-ladder model postulates fixed innovation size and varying innovation speed. If conceivably large (small) innovations take a long (short) time to develop, each nation's product of speed and size can be viewed as an average innovation speed at an internationally identical innovation size.

The first such measure [**R&D/GDP**] is **gross domestic expenditure on R&D as a percentage of GDP**. This measure focuses on the input side and (largely) physical capital, but at the cost of using market values. By focusing on the input side it also includes expenses on failed R&D activities.

The second measure [**RSE/LAB**] is the **number of researchers, scientists and engineers per 10,000 persons in the labor force**. This is an input-based measure that focuses on human rather than physical capital. The pivotal role of human capital is evidenced by the fact that many innovations occur in localized labour markets such as Silicon Valley.

The third measure [**PAT/POP**] is the number of resident (domestic) patent applications per 10,000 population, which I will refer to as the **inventiveness rate**. It has the advantage of focusing on the output side of the R&D process. In addition, it is measured as a quantity and is therefore independent of market prices. Of course, this measure does not capture possible differences in the size or importance of individual innovations. The legal environment also influences the magnitude of this measure: high patent application costs, short patent protection length and diminished patent enforceability tend to decrease the number of patent applications.

5.2 Measuring the R&D Unit Cost

The left-hand side of equation (8) requires a measure of the unit cost of R&D, or at the very least a measure of the productivity of R&D. Optimally, such a measure would specify the average cost of an innovation. The proxies I construct can again be characterized by their relative position in the R&D input-output dimension.

The first measure [**RSE/R&D**] is the inverse of **domestic R&D expenditure per researcher**, expressed in researchers per $mio. This measure can perhaps be viewed as an R&D labor-intensity gauge as long as R&D expenditures largely consists of equipment expenses. Simply put, if more researchers share the same equipment, the innovation process will be costlier. Put another way, it is the "leanness" of the innovation process which reduces the price tag of an innovation.

The second measure [**GRD/UNI**] is the inverse of the **production cost of a university graduate**, defined as the number of graduates (or national equivalent) per $mio of higher education R&D expenditure. If education expenses for graduates are viewed as a subsidy on the market for scientists, supply is increased and private costs of hiring a scientist are reduced. This breaks the wage-performance link, and a "cheap" scientist merely indicates a high level of education subsidies. A country that invests heavily in education of a scientist can thus be expected to offer "cheap" R&D.

The third measure [**R&D/PAT**] is the **average production cost of a patent**, defined as the ratio of gross domestic R&D expenditures (in $mio) to the number of resident patent applications. Patents can be thought of as the output of a successful innovation process. However, legal considerations can lead to a "fractioning" of patent applications so that applications are numerous but small. Countries in which this is the case can be expected to have low **R&D/PAT** unit costs. Griliches (1994) mentions a number of problems with patent data, among them thresholds for patent applications, rising patent "quality", and improving patent protection.

In the absence of ideal measures of R&D intensity and unit costs I have offered six proxies. Each suffers some defects, but obviously one does not want to use this as an excuse for abandoning empirical work or shielding theories from data. In order to explicitly address the shortcomings of my measures I will use their diversity as the basis for an extensive sensitivity analysis.

5.3 Empirical Results

The data analysis is based on the OECD (1992) computerized data base which comprises the OECD member countries for the twelve years between 1980 and 1991. To test the intensity/unit-cost hypothesis one can explore both the time and country dimensions: a single country can be studied over a long period of time or a panel of countries can be studied at a given point in time. In addition, both approaches can be combined.

TABLE 1: R&D INTENSITY AND UNIT COST MEASURES (1980-91 AVERAGES)

Intensity Measures						Unit Cost Measures					
R&D/GDP		RSE/LAB		PAT/POP		RSE/R&D		GRD/UNI		R&D/PAT	
USA	2.77	USA	7.03	JPN	22.5	USA	11.8	CHE	8.1	JPN	0.14
SWE	2.69	JPN	6.54	CHE	5.9	CHE	13.7	USA	8.6	GRC	0.28
DEU	2.68	DEU	5.10	DEU	5.2	SWE	16.6	AUT	9.1	IRL	0.33
CHE	2.58	SWE	4.95	SWE	4.6	ITA	16.7	NLD	9.4	NZL	0.38
JPN	2.56	NOR	4.76	AUS	4.1	BEL	16.9	SWE	10.0	AUS	0.38
GBR	2.27	GBR	4.58	FIN	3.7	GBR	17.0	DEU	10.1	AUT	0.55
FRA	2.21	FRA	4.35	GBR	3.5	DEU	17.0	GBR	10.8	FIN	0.56
NLD	2.10	AUS	4.34	AUT	3.0	FRA	17.1	FRA	14.7	CHE	0.71
BEL	1.67	ISL	4.26	NZL	2.9	NLD	17.1	DNK	15.4	DEU	0.73
FIN	1.60	CHE	4.20	USA	2.9	JPN	17.7	NOR	16.2	GBR	0.81
NOR	1.59	CAN	4.11	FRA	2.2	AUT	17.9	JPN	16.8	SWE	0.82
CAN	1.38	FIN	3.90	NOR	2.1	CAN	19.7	CAN	17.2	DNK	0.82
DNK	1.33	NLD	3.86	DNK	2.1	NZL	21.7	BEL	17.5	NOR	0.89
AUT	1.29	BEL	3.81	IRL	1.9	NOR	22.7	NZL	18.5	ESP	1.10
AUS	1.17	IRL	3.40	NLD	1.6	AUS	23.7	FIN	19.1	ISL	1.29
ITA	1.09	DNK	3.14	GRC	1.1	DNK	23.9	ITA	21.4	FRA	1.37
NZL	0.92	NZL	2.90	ISL	1.0	ESP	24.2	ISL	22.9	NLD	1.59
ISL	0.83	ITA	2.80	CAN	0.9	FIN	26.9	AUS	26.1	USA	1.64
IRL	0.81	AUT	2.30	BEL	0.9	IRL	34.1	GRC	26.5	CAN	2.30
ESP	0.60	ESP	1.75	ESP	0.5	ISL	34.3	PRT	30.4	BEL	2.42
TUR	0.51	GRC	1.10	PRT	0.1	GRC	37.5	ESP	37.9	PRT	3.74
PRT	0.46	PRT	0.96	TUR	0.0	PRT	38.2	IRL	62.4	TUR	4.42
GRC	0.31	TUR	0.85	ITA	†	TUR	66.0	TUR	88.8	ITA	†

† no information available

TABLE 2: CORRELATION MATRICES
(ALL OBSERVATIONS ACROSS TIME AND ACROSS COUNTRIES)

R&D INTENSITY MEASURES				R&D UNIT COST MEASURES			
Measure	R&D/GDP	RSE/LAB	PAT/POP	Measure	RSE/R&D	GRD/UNI	R&D/PAT
R&D/GDP	1.0000	0.8277	0.4773	RSE/R&D	1.0000	0.8286	0.0411
RSE/LAB		1.0000	0.5408	GRD/UNI		1.0000	–.1397
PAT/POP			1.0000	R&D/PAT			1.0000

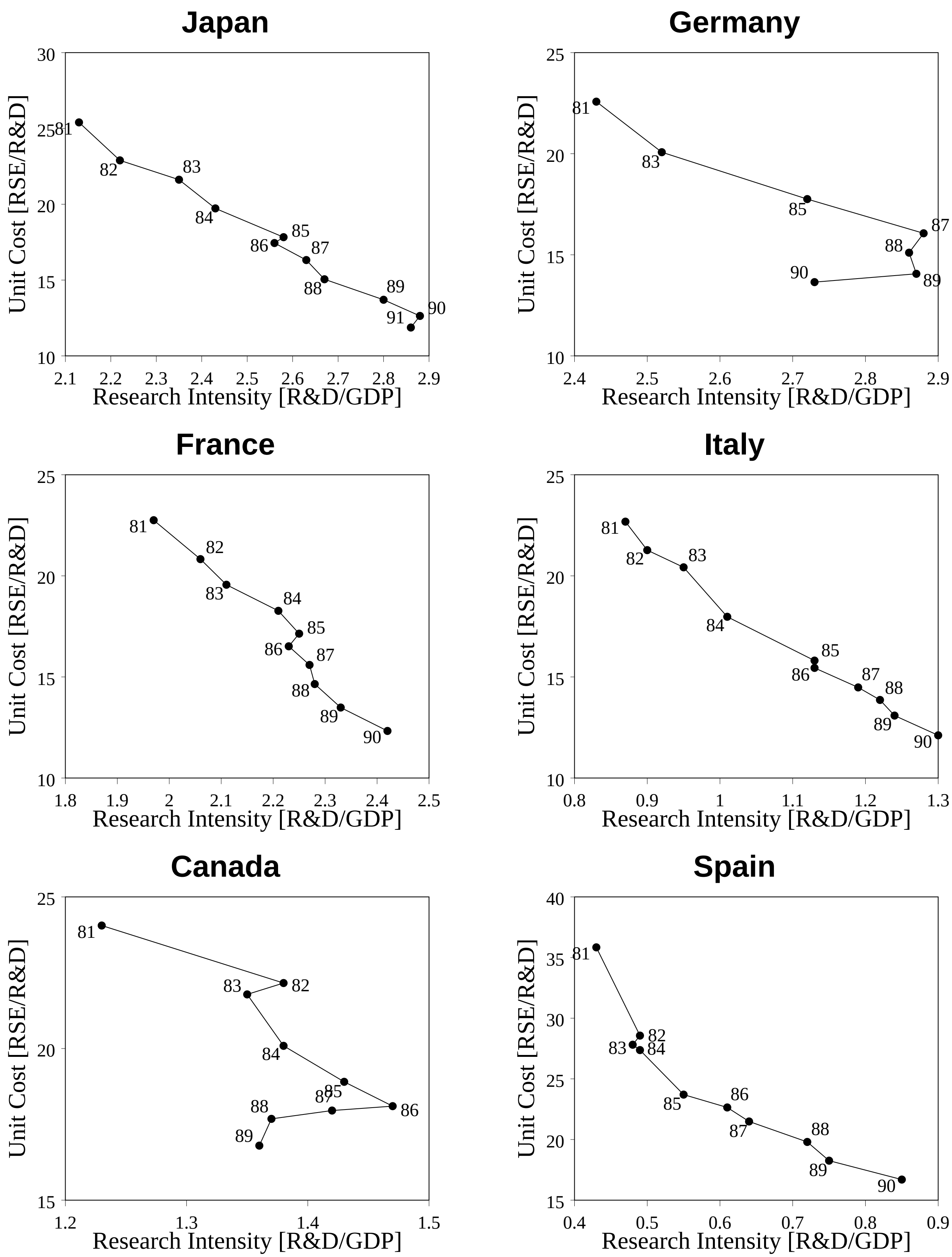
Table 1 presents 12-year averages for my six R&D measures as computed from the OECD data set. Two caveats should be borne in mind. The collection of R&D data is still in its infancy in many OECD countries, and hence the data set contains numerous gaps. There are also different national standards used in the definition of these measures. The left half of table 1 lists the three intensity measures for each country and the right half presents a similar list for the three unit cost measures. The tables are sorted by magnitude so that in the left half of table 1 the countries with the highest research intensities appear at the top and in the right half the countries with the highest unit costs appear at the bottom. In accordance with the hypothesis, R&D-intensive Japan and the United States should appear near the top on both sides of the table. For the intensity measures this can be confirmed. The picture is less clear for the unit cost measures. Japan is at the top of the list for the **R&D/PAT** measure while the United States is not. For the **RSE/R&D** and **GRD/UNI** measures, Japan can be found somewhere in the middle of the table while the United States is at or near the top.

Table 2 reports the correlation coefficients for each possible combination of the two groups of three measures. For the R&D intensity, the first two measures appear to be highly correlated. The correlations with the third measure, the inventiveness rate, are weaker. This may reflect the fact that the patent measure focuses on the output side of R&D while the other two measures focus on the input side. For the R&D unit cost measures the strongest correlation exists between the first two measures, the labour-intensity of R&D and the reciprocal production cost of a scientist. The patent-cost measure shows little or no correlation with the other two measures; one correlation coefficient is indeed slightly negative.

Figures 1–6 give an impression of the dynamics of the R&D equilibrium for six selected countries, depicting the relationship between the **R&D/GDP** intensity measure and the **R&D/RSE** unit cost measure. The conjectured negative relationship can be visually identified. The six countries selected for figures 1–6 were chosen because sufficient data was available for them and because of the magnitude of their R&D. Notably, the time trend for Great Britain (not shown) is reversed, counterindicative to the theory. The time trend was analyzed for all countries and all combinations of R&D measures, and for the vast majority the time trend indicated a simultaneous increase in R&D intensity and decrease in R&D unit costs. The observation that countries experience a widening of the R&D sector (as measured by R&D intensity) is a new benchmark fact of R&D dynamics. Future research has to explain this trend towards higher levels of R&D in OECD countries.

Table 3 presents the OLS regressions for the nine possible combinations of the three intensity measures with the three unit cost measures. (Since the unit cost enters the regression equation as a reciprocal, the unit cost measures appear as their inverse in the following discussion.) To tackle the problem of unequal number of observations, two averages for the period 1981-1985 and 1986-1991 were constructed; this has the additional advantage of smoothing out business cycle effects. Five of the regressions yield conclusive results: [**R&D/RSE**, **R&D/GDP**] and [**UNI/GRD**, **R&D/GDP**] indicate that the **R&D/GDP** intensity measure seems to be working rather well, while [**UNI/GRD**, **RSE/LAB**] confirms the result of [**UNI/GRD**, **R&D/GDP**]. The [**PAT/R&D**, **PAT/POP**] regression that uses output-based R&D measures is also conclusive. Disappointingly, the measures that combine input- and output-based measures perform poorly.

The results of the two strongest regressions appear as figures 7 and 8. In each of the figures the regression is drawn as a solid line. As shown, the positive intercept indicates that in accordance with the theory the real interest rate $\rho = \alpha\zeta$ is positive. When lines are drawn through pairs of data points for individual countries, in the vast majority of cases the slopes are steeper than the



FIGURES 1–6: R&D INTENSITY/UNIT-COST TIME TRACES FOR SIX COUNTRIES

TABLE 3: TESTS OF THE NO-ARBITRAGE CONDITION

Inverse Unit Cost Measure	Intensity Measure R&D/GDP		RSE/LAB		PAT/POP	
	α / $t^*_{\alpha=0}$ / n	β / $t^*_{\beta=0}$ / R^2	α / $t^*_{\alpha=0}$ / n	β / $t^*_{\beta=0}$ / R^2	α / $t^*_{\alpha=0}$ / n	β / $t^*_{\beta=0}$ / R^2
R&D/RSE	0.0238**	0.0170**	0.0239**	0.0070**	0.0457**	0.0011
	(6.912)	(8.546)	(4.842)	(5.842)	(14.650)	(1.964)
	44	0.635	43	0.454	42	0.088
UNI/GRD	0.0182*	0.0311**	0.0305*	0.0096**	0.0630**	0.0011
	(2.579)	(7.559)	(2.637)	(3.295)	(10.009)	(0.956)
	42	0.588	42	0.214	40	0.024
PAT/R&D	2.1704**	–0.2237	1.8966*	–0.0227	0.9801**	0.2526**
	(3.292)	(0.595)	(2.346)	(0.117)	(3.260)	(4.664)
	44	0.008	41	0.000	44	0.341

* significant on 5%-level   ** significant on 1%-level

regression line, which implies a higher average firm size and often a negative real interest rate.

5.4 Sensitivity Analysis

The relationship between R&D unit cost and R&D intensity is not cause and effect. Therefore, there is no natural dependent variable in this model. The choice of inverse unit cost as a dependent variable was a matter of procedural convenience. In addition both dependent and independent variables are measured with error under the assumption of an internationally varying average firm size ζ. Klepper and Leamer (1984) address this choice problem in an errors-in-variables regression and show that the variables measured most with error should be assigned to the right hand side of the regression equation.

Consequently, the five regressions in table 3 that exhibit significant slope estimates need to be subjected to a sensitivity analysis. The problem associated with measurement error in regard to the slope estimates can be explored by a reverse regression.[6] The estimate of the slope obtained from the regression of Y on X and the inverse of the slope's estimate obtained from the reverse regression of X on Y provide lower and upper bounds on the true slope (at least in large samples). Columns (3) and (4) in table 4 reveal that the slope may vary as much as 60% in the first regression and 470% in the third regression.

A second measure of sensitivity is obtained from analyzing the DFBETA measure proposed by Belsley et al. (1980). A DFBETA $B_{i,\beta}$ is the scaled measure of the change in parameter estimate β

[6] See, for instance, Maddala (1977, pp. 292–294) for a treatment of the corresponding statistical methods and problems. Suppose that Y and X are measured with errors. In a regression of Y on X, the OLS estimate of the slope, b_{YX} will underestimate the true slope β. Contrastingly, the OLS estimate of the slope obtained from a reverse regression of X on Y, b_{XY}, will tend to overestimate the true slope β. The asymptotic properties of these estimators are such that $\text{plim}\, b_{YX} \leq \beta \leq 1/\text{plim}\, b_{XY}$.

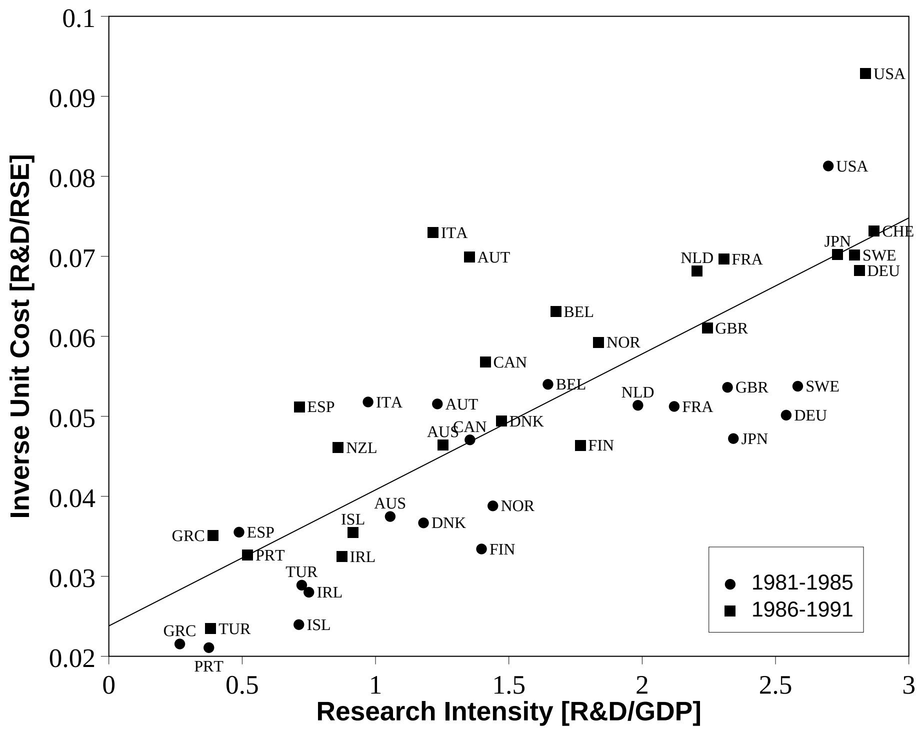


FIGURE 7: CROSS-COUNTRY TWO-PERIOD REGRESSION (R&D/RSE–R&D/GDP)

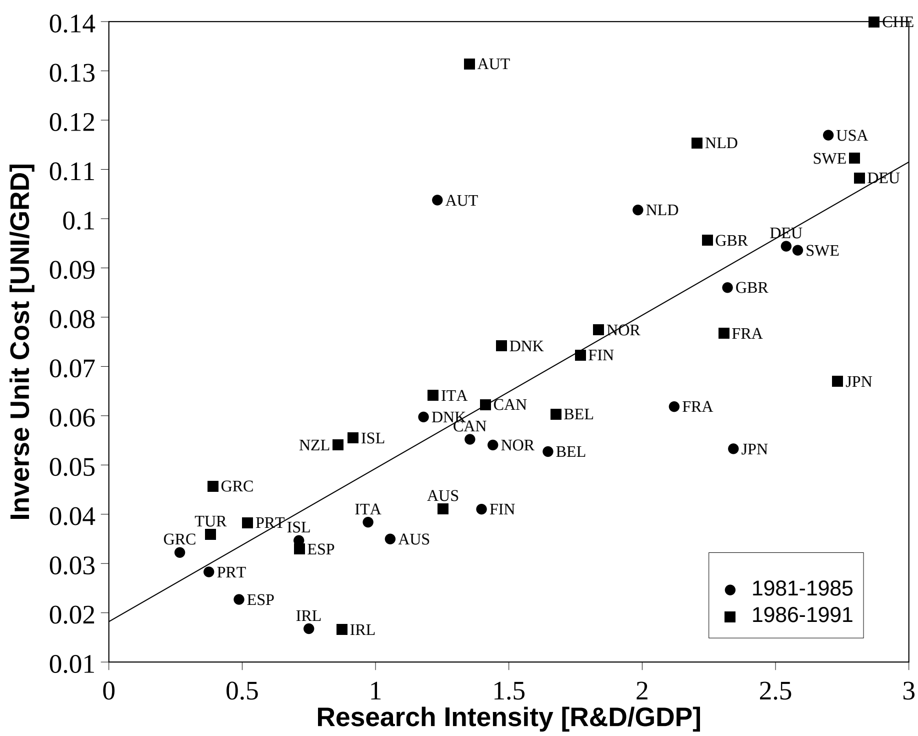


FIGURE 8: CROSS-COUNTRY TWO-PERIOD REGRESSION (UNI/GRD–R&D/GDP)

TABLE 4: REVERSE REGRESSIONS AND SENSITIVITY ANALYSIS

Regression		Reverse Regr.		Sensitivity		
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Y	X	β_{YX}	$1/\beta_{XY}$	$\lvert B_{i,\beta}\rvert > 2/\sqrt{n}$	β_{min}	β_{max}
R&D/RSE	R&D/GDP	0.0170	0.0267	DEU[1], USA[2]	0.0152	0.0178
R&D/RSE	RSE/LAB	0.0070	0.0154	USA[2]	0.0059	0.0076
UNI/GRD	R&D/GDP	0.0311	0.0530	CHE[2], JPN	0.0295	0.0345
UNI/GRD	RSE/LAB	0.0096	0.0448	AUT[2], JPN[2]	0.0087	0.0119
PAT/R&D	PAT/POP	0.2526	0.7404	GRC[2], JPN	0.1496	0.2785

[1] 1981–1985 observation only [2] 1986-1991 observation only

obtained by deleting observation i. Large values of $|B_{ij}|$ indicate observations that are influential in the determination of the j-th coefficient. A size-adjusted cutoff for DFBETAs is given as $2/\sqrt{n}$. Column (5) contains a list of observations for which $|B_{i,\beta}|$ exceeds the suggested cutoff. Columns (6) and (7) in table 4 show the lower and upper bounds of the slope estimates when individual countries (mostly two observations) were deleted. With this method, Greece and Japan had a particularly strong influence on the regressions. The fourth regression, **PAT/R&D** on **PAT/POP**, deteriorates when Japan is excluded and improves substantially when Greece's second observation is excluded. When both countries are excluded at the same time, the regression F-test cannot be rejected ($R^2 = .23$). In conclusion, the input-based R&D measures **R&D/GDP**, **RSE/R&D** and **GRD/UNI** seem to be the most reliable.

6 R&D Differences Revealed by Trade

A key component of the analysis is measuring R&D unit costs. Trade theory, the theory of comparative advantage, has much to say about how unit costs are revealed by the direction of trade flows. For instance, in the Heckscher-Ohlin-Vanek (HOV) framework, a country abundant in R&D factors will have low R&D unit costs and hence will export the services of R&D. However, under the usual factor price equalization assumption, trade equalizes R&D unit costs so that the model is not applicable here. This includes Trefler's (1993) model with a modified version of factor price equalization. Helpman (1984) and Brecher and Choudhri (1984) have provided HOV-style predictions in models without factor price equalization that are well-suited for my task of inferring R&D unit costs from the R&D factor content of trade.

Following Helpman's (1984) exposition, consider a world with N countries that are endowed with J factors of production and that produce goods in K industries. Let w and V be $J\times 1$-vectors for wages and endowments, and let p, Q, X and M be $K\times 1$-vectors for prices, output, exports, and imports. Further let $A(w_c)$ denote the $J\times K$-matrix of factor requirements evaluated at country c's factor prices. F_c^M and F_c^X are the factor services embodied in country c's imports and exports. Let $f(p, V_c)$ be the value production function that is common to all countries. Since importing goods is cheaper than producing them domestically, and because the concavity of the production function requires that a tangent plane at the point $f(p, V_c)$ bounds the production function's surface from above, it must hold that

$$p \cdot (Q_c + M_c) \leq f(p, V_c + F_c^M) \leq f(p, V_c) + [\nabla_V f(p, V_c)] \cdot F_c^M. \tag{9}$$

The properties of the value production function imply that $f(p, V_c) = p \cdot Q_c$ and that the marginal productivity $\nabla_V f(p, V_c)$ equals the wage rate w_c. Then (9) implies

$$p \cdot M_c \leq w_c \cdot F_c^M. \tag{10}$$

Furthermore, zero profits imply that the value of imports $p \cdot M_c$ equals the value of embodied factors $\bar{w}_c \cdot F_c^M$, where $\bar{w}_{cj} \equiv \sum_i (F_{c,i,j}^M / F_{c,j}^M) w_{ij}$ is the average of foreign wages for factor j weighted by the shares of factor content of imports. Substituting $\bar{w}_c \cdot F_c^M$ for $p \cdot M_c$ into the above inequality and exploiting symmetry leads to the following pair of inequalities:

$$(w_c - \bar{w}_c) \cdot F_c^M \leq 0 \tag{11}$$
$$(\bar{w}_c - w_c) \cdot F_c^X \leq 0 \tag{12}$$

Using the fact that net exports of factor services F_c equal $F_c^X - F_c^M$, adding (11) and (12) leads to the theorem $(\bar{w}_c - w_c) \cdot F_c \geq 0$, or equivalently

$$F_{cj} > 0 \iff \bar{w}_{cj} > w_{cj} \tag{13}$$

for a single factor j. This means that country c is a net exporter of the content of those factors that are cheaper in country c than they are on average (using c's import weights) abroad. $\bar{w}_{cj}$ is directed *against* country c, just as research intensities $\bar{\iota}_c$ are directed against country c. Theorem (13) states that *a country will export R&D services that are on average produced at a lower unit cost than abroad.* This leads to a further test of the R&D-intensity/unit-cost theorem by using the observed factor content of trade as an inverse measure of the R&D unit cost.

Due to data limitations, for my empirical work I use a measure of factor content of trade $\bar{F}_c = A(w_{US}) \cdot (X_c - M_c)$ that is based on the U.S. factor requirement matrix. This measure is different from the theoretically sound *actual* factor content of trade measure $F_c = A(w_c)X_c - \sum_{i \neq c} A(w_i) M_{c,i}$ which evaluates the factor requirements at domestic and foreign wage levels.

6.1 The Data

To obtain a measure of R&D content of trade,[7] it is necessary to obtain two data sets: (1) R&D factor usage data by industry for the base country (U.S.), and (2) R&D endowment data on a national level. These two data sets can be merged with the Trefler (1993) data set for 1983, which contains trade data, an input-output table for the U.S. and country consumption shares. Two R&D endowment measures are employed, one focusing on physical capital and one focusing on human capital. The first measure is gross R&D expenditures [referred to as **EXP** in the tables], and the second measure is the number of researchers and scientists [referred to as **RSE** in the tables].

[7] Measuring the R&D content of trade is different from an approach that measures "technology trade" which shows up in the balance of payments and comprises royalties and other license or patent-usage payments. Vickery (1986) has studied the directly observable technology trade. A major drawback of this approach is that it does not have anything to say about the volume of R&D incorporated in traded goods.

For the factor usage table, a complete set of R&D expenses (investments of companies into R&D) for 1983 was obtained from the Standard & Poor's COMPUSTAT database, disaggregated by industry groups. These R&D expenses represent all costs that relate to each firm's development of new products or services; excluded are government-sponsored and customer-sponsored research, engineering expenses, inventor royalties, extractive industry activities, and marketing costs. The disaggregation of researchers and scientists by industry was approximated by using the ILO-type 1 shares for professional and technical employment in the United States.[8]

International R&D data (gross domestic expenditures on R&D and number of research scientists and engineers) are from the OECD (1986) and OECD (1989) studies. These data were only available for 20 OECD countries.

6.2 R&D Content of Trade

Table 5 gives a first impression of the trade in services provided by R&D (column 1) and the abundance of R&D (column 2). Theorem (13) implies that the factor content measure in column (1) is correlated with R&D units costs; therefore the countries in table 5 have been sorted by descending factor content (or ascending unit costs). The figures in this table are percentages of the corresponding national R&D "endowments." The correlation between both measures of R&D factor content is 0.81 and statistically highly significant; this suggests that these measures are reliable.

Using the measure based on R&D expenditures, Japan and Germany are the leading countries. In absolute figures, their calculated R&D service flow embodied in trade is $11.7bn for Japan and $5.9bn for Germany. By-industry country profiles show that in Japan's case the automobile industry is the major contributor to its R&D service-flow surplus, followed to a lesser extent by consumer electronics (radio, TV, telephone), computing machines, and optical instruments. Germany's surplus is sustained by the industries producing automobiles chemicals, drugs, and machinery. The two biggest importers of R&D services are the United States ($1.3bn) and the United Kingdom ($1.0bn). All other countries are in absolute numbers below half a billion dollars. However, the U.S. R&D deficit is small relative to endowment. Here the big R&D-services exporting industries are computing machines and aircraft, while the big industry that is importing R&D-services is the automobile industry. Relative to its endowment, Ireland is also a big net exporter of R&D services embodied in trade. This is explained by Ireland's strength in the computing machines industry. At the bottom of table 5, Greece imports R&D services primarily through the purchase of automobiles.

When scientists are taken as a measure, the magnitudes of R&D service flows relative to endowment are generally smaller, and the directions of R&D flows are reversed for 7 out of 20 countries. Japan and Germany are again the big exporters in absolute figures (the equivalent of over 7,000 and over 4,000 scientists), but Canada and the Netherlands occupy, third and fourth places (1,870 and 1,421 scientists, respectively). The big importers are the U.S. (8,397), the U.K. (2,931)

[8] The lack of comprehensive cross-country R&D data makes it difficult to construct better measures. For example, Coe and Helpman (1993) fill the numerous gaps for many OECD countries with regression estimates. I have constructed a measure of the R&D capital stock for the U.S. using the perpetual inventory model with a 12 year horizon and a 10% depreciation rate. However, for the U.S. the capital stock is highly correlated with the one-year R&D expenditure figures. Compared to the Acs and Audretsch (1990, pp. 165–175) data set of innovations introduced in 1982, the most striking discrepancy in terms of industry significance is that the motor vehicle industry introduced a substantially lesser share of innovations than its share of R&D expenses suggested.

TABLE 5: R&D FACTOR CONTENT OF TRADE AND R&D ABUNDANCE (RELATIVE TO NATIONAL ENDOWMENT, IN %)

R&D Expenditures				Researchers & Scientists			
Country	(1)	(2)	(3)	Country	(1)	(2)	(3)
Ireland	42.66	-157.58	–	Netherlands	6.59	-31.06	–
West Germany	29.86	7.59	+	Denmark	6.33	-53.87	–
Japan	29.13	19.68	+	Ireland	5.85	-14.40	–
Sweden	11.69	6.79	+	Canada	5.36	-78.75	–
Netherlands	9.98	-8.66	–	Norway	3.27	-31.00	–
Italy	5.06	-65.19	–	Sweden	3.24	-21.55	–
Switzerland	4.21	-53.15	–	West Germany	3.20	-3.55	–
France	2.67	-8.90	–	Finland	2.08	-13.99	–
Belgium	2.36	-68.09	–	Japan	1.61	44.24	+
United States	-1.15	15.69	–	Italy	0.80	-38.69	–
Canada	-5.67	-54.38	+	Yugoslavia	-0.39	45.28	–
UK	-6.98	2.12	–	United States	-1.18	1.95	–
Yugoslavia	-12.45	-88.50	+	France	-1.68	-29.15	+
Spain	-16.61	-221.85	+	Switzerland	-2.39	-104.40	+
Finland	-27.96	-67.97	+	UK	-2.81	-1.50	+
Denmark	-28.69	-99.39	+	Belgium	-3.25	-73.07	+
Norway	-31.40	-53.00	+	Spain	-6.92	-164.94	+
Austria	-40.65	-90.94	+	Austria	-8.06	-122.12	+
Portugal	-136.52	-245.94	+	Portugal	-10.47	-51.23	+
Greece	-166.23	-482.64	+	Greece	-25.89	-190.55	+

(1): $100 \cdot \bar{F}_{fc}/V_{fc}$ (2): $100 \cdot (V_{fc} - s_c V_{fw})/V_{fc}$ (3): sgn$\{(1)\}=$sgn$\{(2)\}$

and France (1,557).

Note that HOV does poorly. The agreement between R&D service flows and R&D abundance is indicated by the sign test in column 3. The sign test fails in roughly half of all cases. Failure of HOV suggests the need for models like Brecher and Choudhri (1984) and Helpman (1984).

6.3 Investigation of the No-Arbitrage Condition

The R&D intensity/unit-cost hypothesis can be investigated by regressing the R&D content of trade calculated above, expressed as a percentage of the national endowment, on the standard measures of R&D intensity developed in section 5.

Factor content of trade is measured relative to a country's endowment as $\bar{F}_{cj}/V_{cj}$. As countries cannot export factor services in excess of their factor endowment, this measure lies in the interval $(-\infty, 100\%]$. Research intensities, on the other hand, lie in the interval $[0, 100\%]$ when expressed as GDP or labor force ratios. This suggests a non-normal, skewed error structure in a regression of factor contents of trade on R&D unit costs. I address this skewness by taking the log of $\bar{\iota}_c$. Table 6 summarizes the main findings for an ad-hoc regression equation $(\bar{F}_c/V_c) = \alpha + \beta \log(\bar{\iota}_c)$, with t-statistics given in parentheses. A positive β indicates support for the theory; α can take either sign. All six βs have the predicted sign, thus lending support for the theory. In addition,

TABLE 6: TESTS OF THE NO-ARBITRAGE CONDITION WITH FACTOR CONTENT OF TRADE DATA

Inverse Unit Cost Measure	Intensity Measure: R&D/GDP α / $t^*_{\alpha=0}$ / n	R&D/GDP β / $t^*_{\beta=0}$ / R^2	RSE/LAB α / $t^*_{\alpha=0}$ / n	RSE/LAB β / $t^*_{\beta=0}$ / R^2	PAT/POP α / $t^*_{\alpha=0}$ / n	PAT/POP β / $t^*_{\beta=0}$ / R^2
F_{EXP}	–39.33**	61.47**	–115.1**	78.44**	–38.25**	27.08*
	(4.148)	(4.652)	(5.846)	(5.385)	(3.027)	(2.873)
	19	0.560	19	0.630	18	0.340
F_{RSE}	–4.166*	7.969**	–13.60**	9.761**	–3.219	2.475
	(2.612)	(3.584)	(3.785)	(3.704)	(1.495)	(1.541)
	19	0.430	19	0.447	18	0.129

five of them are statistically significant. The OLS estimates disguise the underlying data and can be somewhat misleading.

Figures 9 and 10 illustrate the regressions in the first row and first two columns of table 6 As can be seen, the observations with a low research intensity strongly influence the regressions. The White-test χ^2-statistic for heteroskedasticity is somewhat significant in the first regression, and insignificant in all other regressions. Although it may be tempting to delete Greece and Portugal, these countries provide important insight into the R&D performance at the lower end of the activity spectrum. The fact that OECD countries are not spread out more on the R&D-intensity spectrum lends increased significance to these few observation points.

7 Conclusions

The "quality-ladder" growth model suggests a no-arbitrage steady-state condition that can be subjected to empirical scrutiny. By introducing identifying restrictions on this no-arbitrage condition, a measurable relationship between R&D intensity and R&D unit costs can be established. Two different empirical approaches have been pursued in this paper to study this relationship: one based on direct measures derived from an OECD database, and another one based on the R&D content of trade in a world without factor price equalization. The empirical results from a multi-country panel generally support this integral element of the "quality ladder" growth theory: *R&D unit costs are inversely related to national R&D activity levels.* Specifically, countries with high R&D activity levels—like the U.S. or Japan—exhibit low R&D unit costs, while countries with low R&D activity levels—like Greece and Portugal—exhibit high R&D unit costs.

A problem that has not been addressed in this paper is that R&D is increasingly carried out by multinational corporations. This causes problems both theoretically (in modeling knowledge spillovers) and empirically (by using country-based R&D measures). Moreover, in modeling the R&D process, more attention has to be paid to heterogeneity on the firm level and to explicit intra-industry, inter-industry, and international knowledge spillovers. On the empirical side the need for more comprehensive, longer-period, and better disaggregated R&D data is clearly visible.

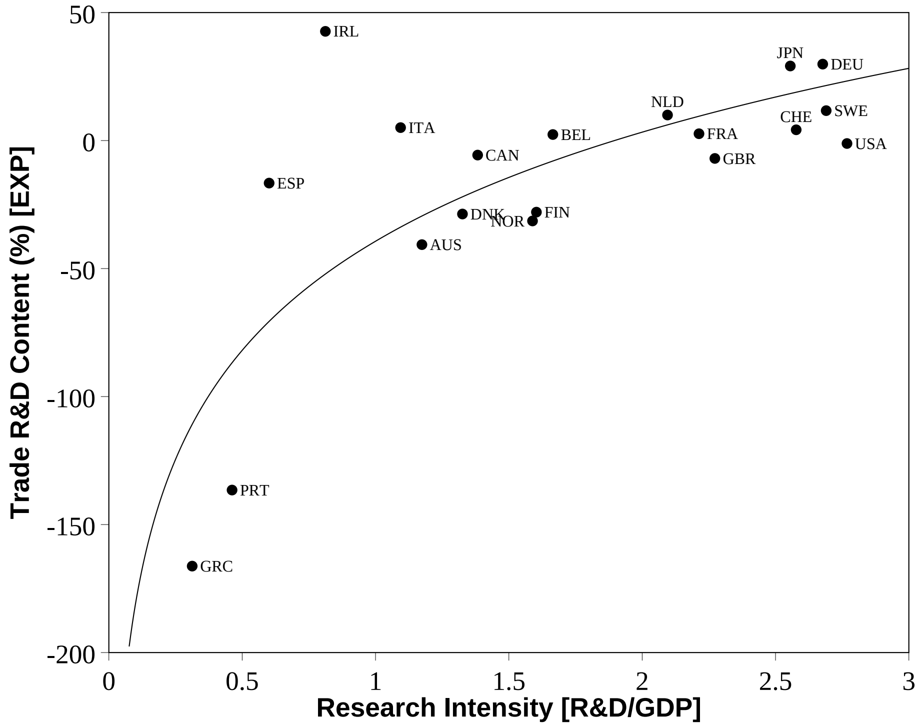


FIGURE 9: FACTOR CONTENT OF TRADE AS UNIT COST MEASURE

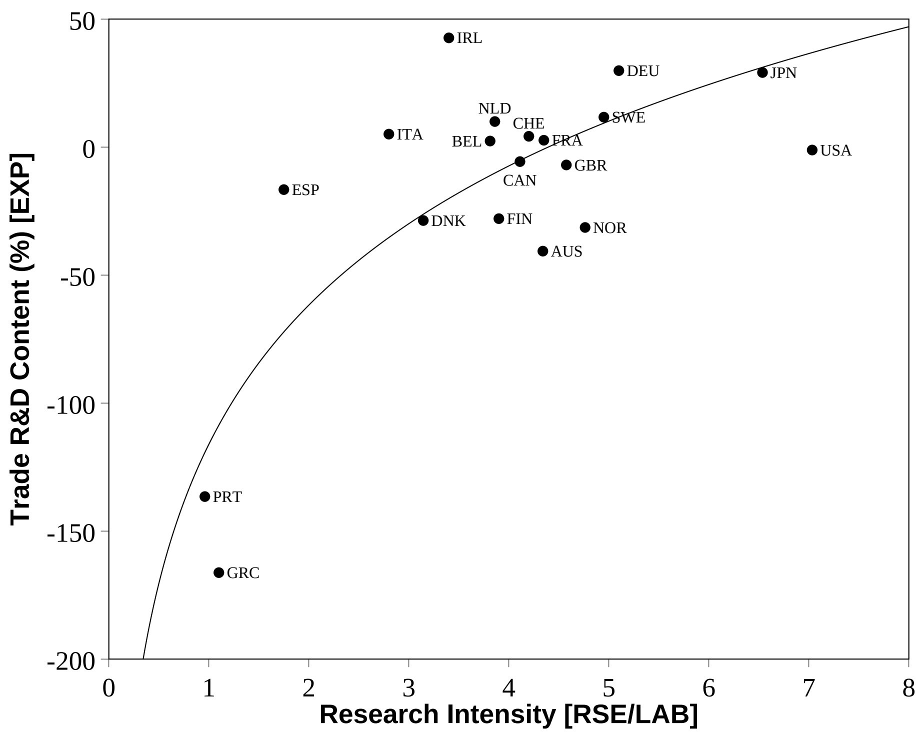


FIGURE 10: FACTOR CONTENT OF TRADE AS UNIT COST MEASURE

The empirical findings of this paper have also raised a new question. Almost all OECD countries continuously increase their R&D intensity over time. If this observed trend can also be confirmed over longer periods of time, it creates a new theoretical challenge for models of endogenous technological growth.

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