Indicators for complex innovation systems: A scale-independent view

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Abstract

Many traditional performance indicators are derived from the ratio of two measures. Sometimes they are used to rank members of an innovation system and the results are used to inform public policy decision makers.

It has been shown that a scaling or power law relationship exists between the numerator and denominator of three traditional performance indicators - national wealth, R&D intensity and scientific impact [Katz, J.S., 2006. Indicators for complex innovation systems. Research Policy 35, 893–909][1]. Scaling relationships are a unique type of nonlinear relationship expected of measures made of complex systems.

The systemic scaling relationships between GERD and GDP across members of the European and Canadian innovation systems are used to construct scale-independent R&D intensity indicators. The differences between the rankings of the members of each system using traditional and scale-independent R&D intensity indicators are explored and discussed. It is shown that both indicators are equivalent when a linear correlation exists between the numerator and denominator. In all other instances, traditional indicators are not normalized for size while scale-independent indicators are normalized properly.

Traditional indicators are based on linear notions and help perpetuate the linear model of innovation. Scale-independent indicators are based on nonlinear properties expected of a complex system. They can be used to answer question requiring knowledge of the amount a member contributes to a system given its size and the nature of the system in which it resides. They provide decision makers with policy relevant, scale-independent views of complex innovation systems.

[1] A preprint is available at http://www.sussex.ac.uk/Users/sylvank/pubs/ICIS-RP.pdf

1. Introduction

An innovation system is composed of individuals and organizations that directly and indirectly invest time, energy and resources in the production of scientific and technical knowledge. Performance indicators are used to rank members of these systems. A rank ordered list is sometimes used to inform public policy decision makers. For example, national wealth (GDP per capita), R&D intensity (% GDP spent on R&D) and research impact (citations per paper) are performance indicators used to rank groups such as countries, regions, institutions and research teams.

Consider the difference in how decision makers in the early 1990s might have been influenced when forming public policy if they were given the following data. Tables 1a and 1b rank the countries and provinces of the European and Canadian innovation systems using two methods of measuring R&D intensity: (a) the traditional method and (b) a scale-independent method (Katz 2006).

Table 1a - European Research Area R&D Intensity (1990)

Rank	Country	Traditional	Country	Scale-independent
1	Sweden	2.74	Sweden	2.25
2	Germany	2.67	Finland	1.79
3	France	2.37	Netherlands	1.49
4	United Kingdom	2.15	Denmark	1.47
5	Netherlands	2.07	Belgium	1.27
6	Finland	1.88	Germany	1.26
7	Belgium	1.59	France	1.21
8	Denmark	1.57	Austria	1.17
9	Austria	1.39	United Kingdom	1.13
10	Italy	1.29	Ireland	0.94
11	Ireland	0.83	Italy	0.67
12	Spain	0.82	Spain	0.50
13	Portugal	0.51	Portugal	0.46
14	Greece	0.34	Greece	0.30

Note: Luxemburg not included due to sparse data during time interval

Table 1b - Canadian R&D Intensity (1990)

Rank	Province	Traditional	Province	Scale-independent
1	Quebec	1.69	Nova Scotia	1.33
2	Ontario	1.57	Quebec	1.22
3	Nova Scotia	1.39	NFL	1.15
4	NFL	1.12	Ontario	1.05
5	Manitoba	1.09	Manitoba	0.99
6	Alberta	1.07	New Brunswick	0.98
7	New Brunswick	1.00	PEI	0.91
8	British Columbia	0.97	Saskatchewan	0.88
9	Saskatchewan	0.95	Alberta	0.85
10	PEI	0.74	British Columbia	0.76

NFL – Newfoundland and Labrador; PEI – Prince Edward Island

The traditional R&D intensity indicator is expressed as the gross expenditure on R&D expressed as a portion of GDP. The *scale-independent* or scale-adjusted R&D intensity indicator is corrected to account for the scaling correlations between the numerator and denominator of the indicator. Scaling correlations are expected between primary measures used to characterize innovation systems (Katz 2006) if they are considered to be *complex systems* (Baranger 2001). Scale-independent indicators and complex systems will be discussed in detail shortly.

An examination of the tables reveals some interesting differences. The traditional R&D intensity indicator lists Germany, France and the UK in 2nd, 3rd and 4th places, respectively. Using the scale-adjusted indicators they move to 6th, 7th and 9th places, respectively. Quebec and Ontario in the Canadian system move from 1st and 2nd to 2nd and 4th. The bottom five countries in the European system showed little change with Italy and Ireland interchanging ranks. More shuffling of provinces occurred in the lower half of the Canadian table. Intuitively it seems possible that the two rankings might have influenced decision makers differently. Which view is the right view?

Consider the following situation. Assume we want to compare the amount two individuals spend on food and security. One individual earns $100,000 per year and the other $1,000,000 per year. If the lower earner spends 10% of his income on food and 1% on security is it reasonable to expect the larger earner to spend the same percentage of his income on these items?

Probably not. Speaking strictly in caloric units both individuals will have similar food requirements, however the larger earner can afford to purchase better quality and more exotic foods but it is unlikely that he would spend 10% of his income or $100,000/year on food. It is likely that he will have more possessions and therefore spends more on security than the lower income earner. Intuitively one can see how some types of expenditures and incomes might increase or decrease in a disproportional or non-linear manner across members of a community.

It will be argued that innovation systems are complex systems that are expected to exhibit scaling correlations and distributions. It will be shown that GERD and GDP for countries and provinces in the European and Canadian innovation systems exhibit scaling correlations over time and at points in time. This relationship allows us to show that the traditional R&D intensity indicator also scales with size illustrating that it is not normalized for size and therefore not suitable for comparing groups of different sizes. On the other hand the scale-independent R&D intensity indicator has been adjusted for scale and it can be used to compare members of vastly different sizes.

2. Complex innovation systems

Although a complex system is difficult to define it has recognizable characteristics (Amaral; Ottino 2004; Baranger 2001). Amongst other things a complex system

- has a dynamic structure with interdependent constituents that interact in complex and non-linear ways
- is open in the sense that information flows across its boundaries which in turn are difficult to clearly identify
- possesses structures that span many scales
- exhibits emergent behaviours and patterns that are not caused by a single entity in the system but may arise from simple rules
- can self-organize, i.e. its emergent properties may change its structure or create new structures
- is composed of complex subsystems.

A special of kind of complex systems was created to accommodate living beings (Baranger 2001). They are *complex adaptive systems* (CAS) capable of both changing themselves to adapt to a changing environment and changing the environment to suit themselves. Among other strategies they use the interplay between competition and co-operation to survive and evolve.

Most, if not all, complex systems have a propensity to exhibit scaling properties (Carlson; Doyle 2002; Newman 2000). The signature of a scaling property is a *power law correlation* between variables of the system or *power law probability distribution* of a property of the system. Formally a power law is defined by $F(x) \propto x^{\alpha}$ where the variable of interest $x \in [x_0, x_n]$ and n > 0 (Newman 2005). The exponent, α, of the power law relationship is called the *scaling factor*. It can be used as an indicator of a scaling property of a system. For example, the scaling factor of objects like clouds, plants and the World Wide Web is between 1.0 and 3.0 (Strogatz 2005).

Scaling correlations and distributions are a unique type of nonlinear relationship that looks linear when plotted on a log-log scale. Scaling correlations are expected in systems where the primary measures exhibit power law probability distributions such as the distribution of income (Pareto 1897), scientific productive & impact (de S. Price 1963), and collaboration and Web links (Newman 2005).

Scaling correlations can occur as a result of aggregating primary measures that exhibit scaling probability distributions into groups (Katz; Cothey 2006)[2]. For example, the indegree probability distribution of Web pages scales. When Web-pages are aggregated into groups by domains, countries and provinces this produces a scaling correlation between indegree and size. Also, it has been shown that the Hirsch index, an indicator that has created a stir in the evaluation community recently, scales with papers and citations when individuals are aggregated into groups (Egghe; Rousseau 2006; van Raan 2006). Hence aggregating expenditures and incomes that have power law probability distributions into measures of group size such as GDP is expected to show scaling correlations with other measures such as GERD.

Scaling relationships are produced by a variety of mechanisms (Mitzenmacher 2003) ranging from completely deterministic processes (strictly rule based) to completely non-deterministic processes (stochastic or random). Many scaling relationships are produced by mixed processes i.e. rule-based and random processes interwoven. The scaling factor for deterministic processes is predictable from the rules while the scaling factor for mixed processes is frequently expected and unpredictable but measurable.

3. The scaling properties of R&D intensity

The R&D intensity performance indicator is used to compare members of an innovation system (EC 2005). This indicator is derived from the ratio of two primary measures: GERD and GDP. Assume a power law correlation exists between these measures, i.e. $\mathrm{GERD} \propto \mathrm{GDP}^{\alpha}$. Then using the exponent laws[3] we would know that $\mathrm{GERD}/\mathrm{GDP} \propto \mathrm{GDP}^{\alpha-1}$. Hence we could conclude that the traditional R&D intensity scales with size measured using GDP and therefore is not normalized for size.

In the unique case when $\alpha=1$ which only occurs when GERD scales linearly with GDP the scaling factor for the scaling correlation between R&D intensity and GPD would be equal to zero. This indicates that R&D intensity is constant with increasing size. In this case and only this case the traditional R&D intensity and the scale-adjusted R&D intensity indicators will give equivalent ranks. In all other instances the R&D intensity has to be adjusted for scaling trends before it can be used to accurately answer policy relevant questions such as “How much a member of a system is contributing to the community given it size?”

[2] A preprint is available at http://www.sussex.ac.uk/Users/sylvank/pubs/WICIS.pdf
[3] See http://mathworld.wolfram.com/ExponentLaws.html

3.1 Scaling with time

The GERD and GDP of members of an innovation system and the system as a whole tend to exhibit exponential growth due to underlying growth regularities such as interest rates and inflation. It has been shown that a pair of exponential processes coupled through a common variable such as time will exhibit a power law correlation where the scaling factor is given by the ratio of the exponents of the exponential growth processes (Katz 2005; 2006).[4]

For example, between 1981 and 2000 the European GDP and GERD grew exponentially with exponents of 0.052 and 0.051, respectively. During the same time period the Canadian GDP and GERD grew exponentially with exponents of 0.053 and 0.076, respectively. Using the law of coupled exponentials it was predicted that the scaling relationship between GDP and GERD for the European and Canadian innovation systems should be 0.052/0.051 = 1.027 and 0.076/0.053 = 1.418.

Figures 1a and 1b are log-log plots of the 1981-2000 GERD and GDP for the European and Canadian innovation systems. The scaling factors had measured values of 1.034 ± 0.028 and 1.418 ± 0.028, respectively. The scaling relationship for the European system is nearly linear. Every time the European GDP doubled, its GERD tended to increase 2.04 times ($2^{1.027}$). In comparison every time the Canadian GDP doubled its GERD tended to increase 2.67 times ($2^{1.418}$).

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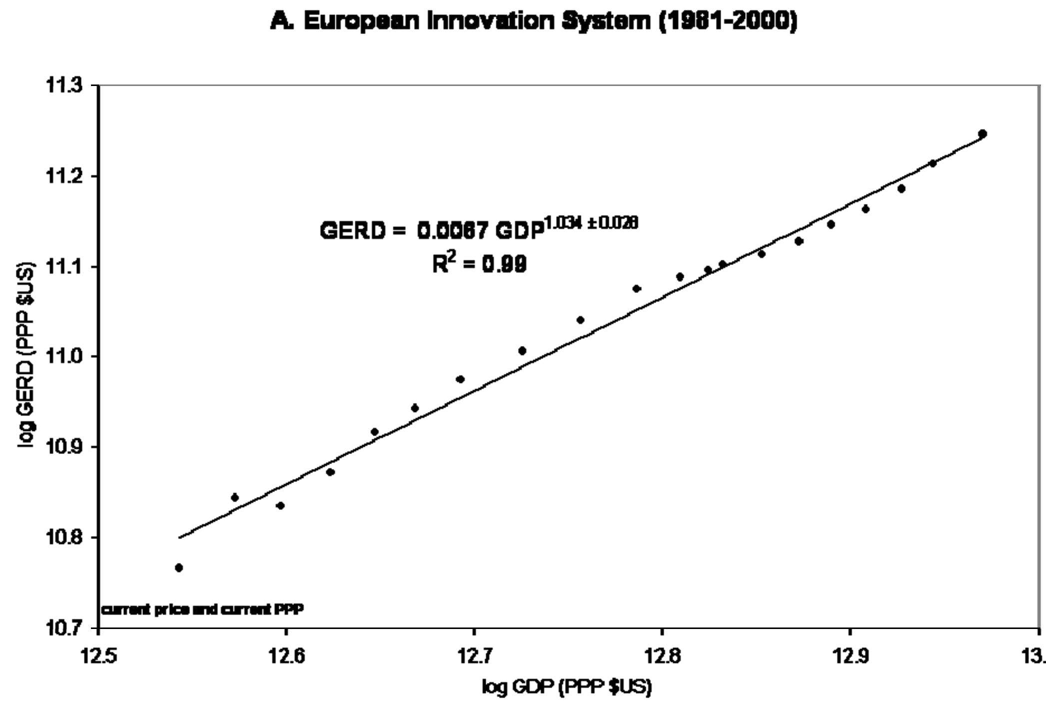
[4] Assume we are given any two exponential processes $x = ae^{pt}$ and $y = be^{qt}$. Using these two relationships $e = (x/a)^{1/pt} = (y/b)^{1/qt}$ and thus $(x/a)^{1/p} = (y/b)^{1/q}$, therefore it can be seen that $y = (b/a)^{q/p} x^{q/p}$ which has the form of $F(x) \propto x^{\alpha}$. In other words, any pair of coupled exponential processes will exhibit a power law correlation with exponent, $\alpha = q/p$, and intercept, $s = b/a^{q/p}$, that are predictable from the exponents and intercepts of the individual exponential processes. This relationship holds even if the two processes are delayed in time with respect to each other or if they have different starting values at t = 0.



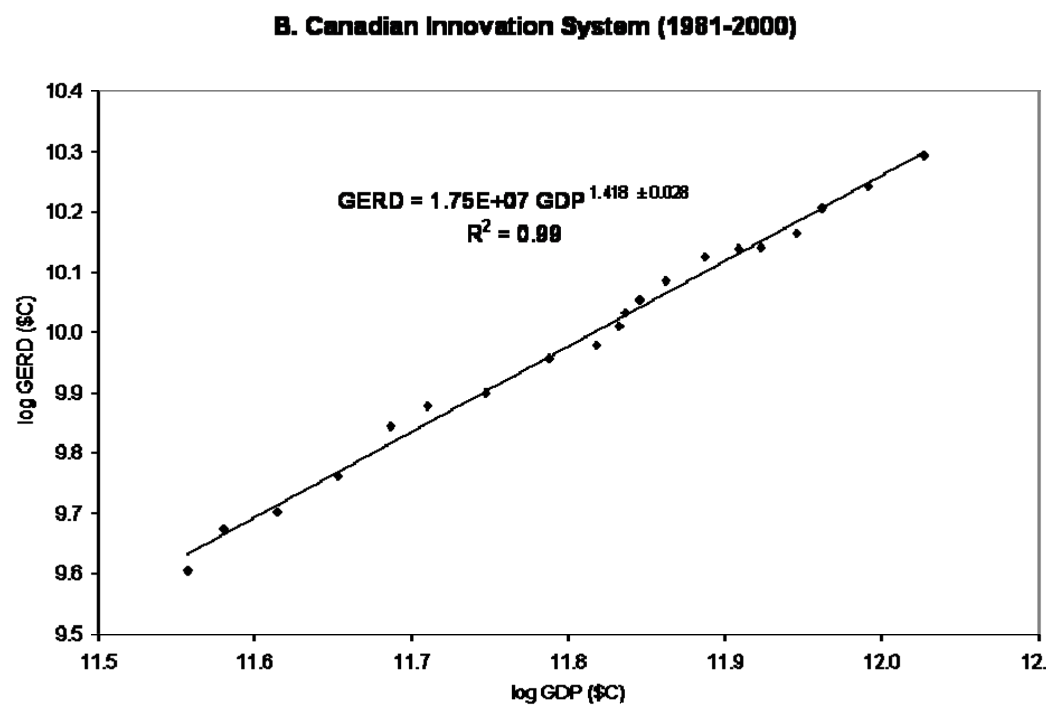


Figure 1 – Scaling correlation between GERD and GDP between 1981-2000 for the (a) European and (b) Canadian innovation systems

Using these scaling relationships the predicted scaling correlation between R&D intensity and GDP is 0.027 and 0.418. The measured values were 0.034 ± 0.028 and 0.418 ± 0.028, respectively.

The R^2 values for the R&D intensity scaling relationship with GDP are smaller than those measured for scaling correlation between GERD and GDP. This is expected because the exponential trends are not ideal. In addition rounding errors are produced when the ratios are calculated. Also, there is a tendency for the confidence of measured scaling relationships to decrease as the size of the groups decrease[5]. The result is lower confidence in the measured scaling trends between R&D intensity and GDP compared to the confidence in the scaling relationship between GERD and GDP. However, since the predicted and measured values are very close we can be confident that in these instances R&D intensity tends to scale with size.

The sign and magnitude of the scaling factor can be used as indicators. For example, when the sign is positive we know that both GERD and GDP are either growing or declining exponentially and when the sign is negative either GERD or GDP is growing exponentially while the other is declining exponentially. If $\alpha > 1$ then GERD is growing faster than GDP, if $\alpha < 1$ then GERD is growing slower than GPD and if $\alpha = 1$ then GERD is growing at the same rate as GDP.

Table 2a and 2b give the scaling relationships between GERD and GDP for European countries and Canadian provinces listed in descending order of α. The population in 2000 is given as another measure of the size of the country or province.

[5] For example, scaling correlations exists between citations and papers at points in time measured across disciplines, countries, sectors, regions (Katz 2000) and research groups (van Raan 2006a). van Raan argues that at the level of the research group the variance is sufficiently large to make it unnecessary to adjust for the scale effects. However, he measured the scaling correlation between citation and papers across 157 research groups to be 1.25 with $R^2 = 0.69$. This suggests with reasonable certainty that scaling does occur at the level of the research group and therefore scientific impact scales with size too.

Table 2a - European GERD-GDP Scaling Factors (1981–2000)

Country	Pop. ('000)	α	se*	R^2
Greece (EL)	10,917	2.58	± 0.06	0.99
Finland (FIN)	5,176	2.05	± 0.05	0.99
Portugal (P)	10,225	1.84	± 0.05	0.99
Denmark (DK)	5,338	1.82	± 0.02	1.00
Spain (E)	39,927	1.75	± 0.06	0.98
Sweden (S)	8,872	1.57	± 0.05	0.98
Austria (A)	8,012	1.50	± 0.03	0.99
Ireland (IRL)	3,799	1.49	± 0.05	0.98
Belgium (B)	10,246	1.26	± 0.03	0.99
France (F)	60,594	1.11	± 0.04	0.98
Italy (I)	57,762	1.11	± 0.09	0.91
Netherlands (NL)	15,922	1.03	± 0.04	0.98
Germany (D)	82,188	0.87	± 0.05	0.95
United Kingdom (UK)	58,643	0.73	± 0.02	0.99

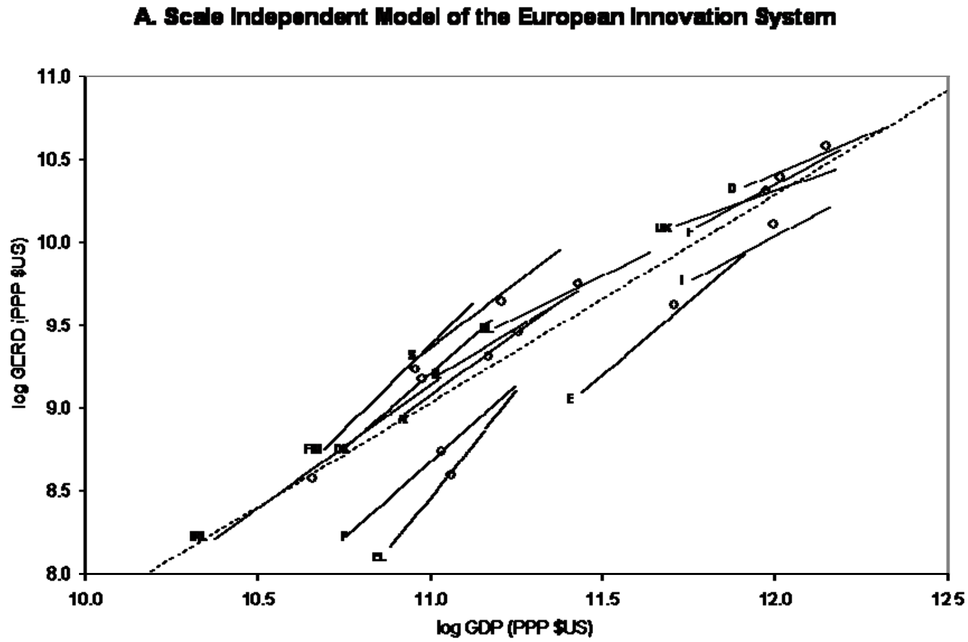
* se is the standard error for α

Table 1b - Canadian GERD-GDP Scaling Factors (1981 – 2000)

Province	Pop. ('000)	α	se*	R^2
Quebec (QC)	7,382	1.84	± 0.05	0.99
British Columbia (BC)	4,060	1.40	± 0.06	0.97
New Brunswick (NB)	756	1.38	± 0.14	0.85
Saskatchewan (SK)	1,022	1.35	± 0.12	0.88
Ontario (ON)	11,698	1.33	± 0.04	0.98
Newfoundland & Labrador (NL)	538	1.21	± 0.09	0.90
Nova Scotia (NS)	942	1.14	± 0.07	0.94
Alberta (AB)	3,010	1.09	± 0.08	0.91
Prince Edward Island (PE)	138	1.09	± 0.07	0.94
Manitoba (MB)	1,146	1.06	± 0.08	0.92

* se is the standard error for α

Figures 2a and 2b are collections of log-log GERD versus GDP plots representing the scaling correlation for members of each system. The values of α in the tables are the slopes of the lines in the figures and the circles represent the actual 1990 values. The dotted lines in the figures will be discussed later.



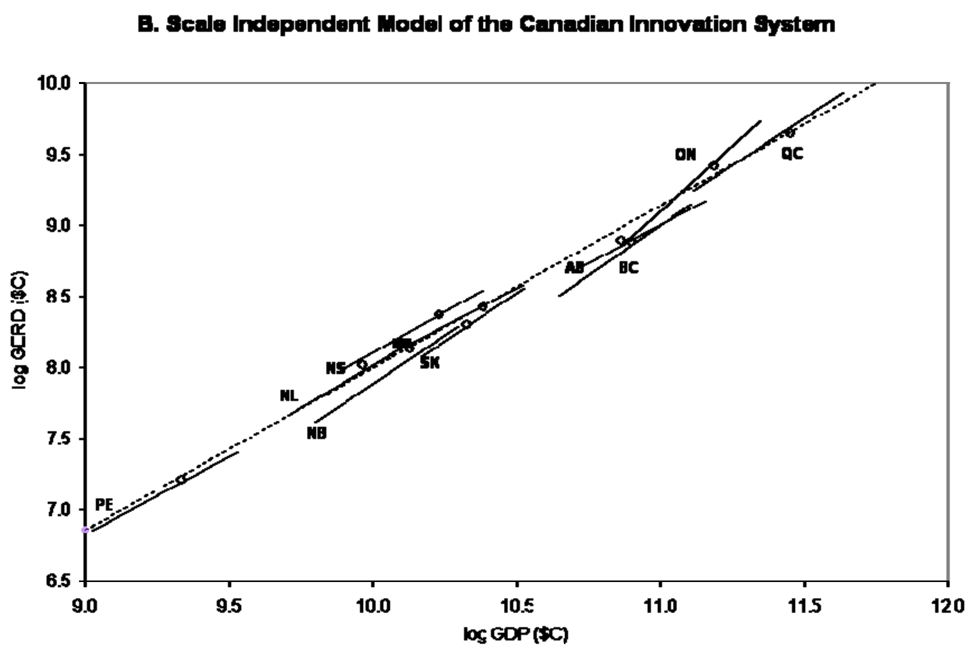


Figure 2 – Collection of scaling correlation for members of the (a) European and (b) Canadian innovation systems

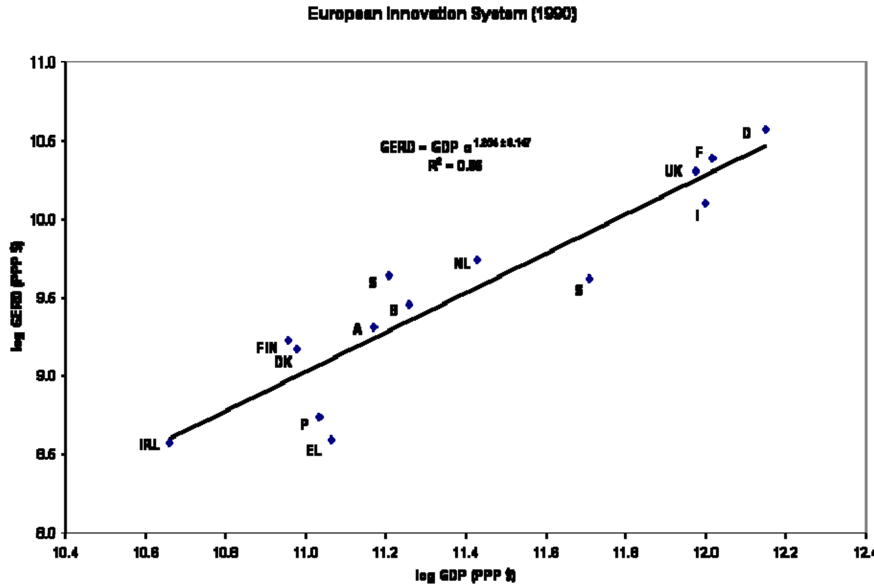
3.2 Scaling at points in time

GERD & GDP can scale across members of an innovation system at a point in time (Katz 2005; 2006). Figure 3a is a log-log plot of 1990 GERD & GDP values for nations in the European innovation system. 1990 was chosen because it is halfway through the time interval under consideration. The circles in Figure 2a and the dotted lines correspond with the points in Figure 3a and the regression line. Figure 3b is a similar plot for Canadian provinces.

The GERD-GDP scaling factor is called a *systemic scaling factor* because it quantifies the relationship between these primary measures across members of a system at a point in time. The systemic scaling factor is not determined by any individual entity in the system. It evolves from the complex interaction between its members and between itself and other systems. It is an emergent property of the system.

The systemic GERD-GDP scaling factor tells us how the expenditures on R&D by members of an innovation system tend to scale with the size of the member economies. Unlike the scaling relationship between GERD and GDP over time, which is predictable, this scaling relationship is not predictable; however, it is measurable.

The measured systemic GERD-GDP scaling factor for the European system was 1.254 ± 0.147. This indicator tells us that as the size of the national economy doubled the systemic tendency was for GERD to increase by 2.4 times ($2^{1.254}$). In the Canadian system GERD tended to increase by 2.2 times ($2^{1.127}$) for each doubling. These scaling correlations can be used to predict the scaling factor for power law relationships between traditional R&D intensity and GDP by using rules of powers given earlier. The expected values were 0.254 and 0.127. The measured values were 0.25 ± 0.15 and 0.13 ± 0.04 for Europe and Canada, respectively.



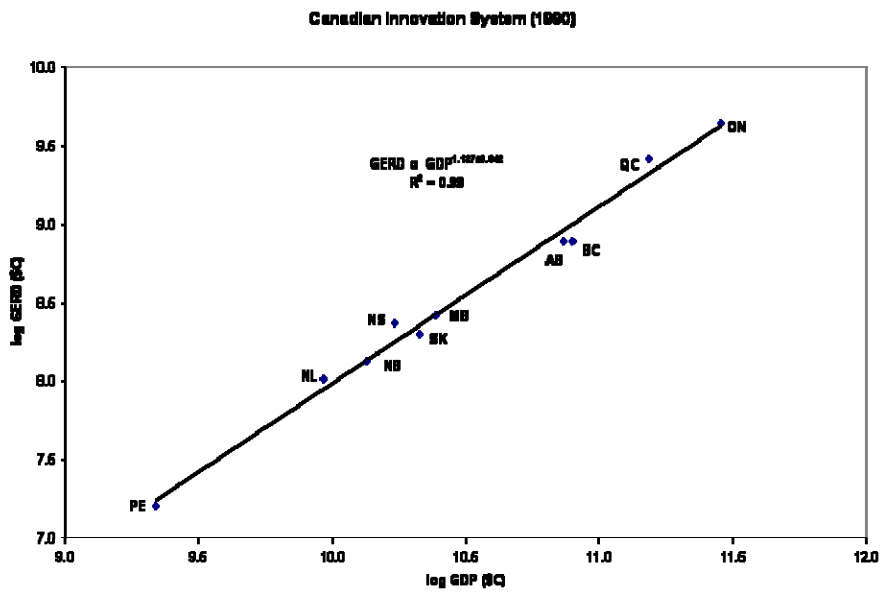


Figure 3 – The systemic scaling relationship between GERD and GDP across members of the (A) European and (B) Canadian innovation systems in 1990.

3.3 Evolution of the systemic GERD-GDP scaling correlation

The systemic GERD-GDP scaling factor was measured for each year between 1981 and 2000 for the European and Canadian innovation systems. Figure 4 graphs the value of the systemic scaling factors at each point in time.

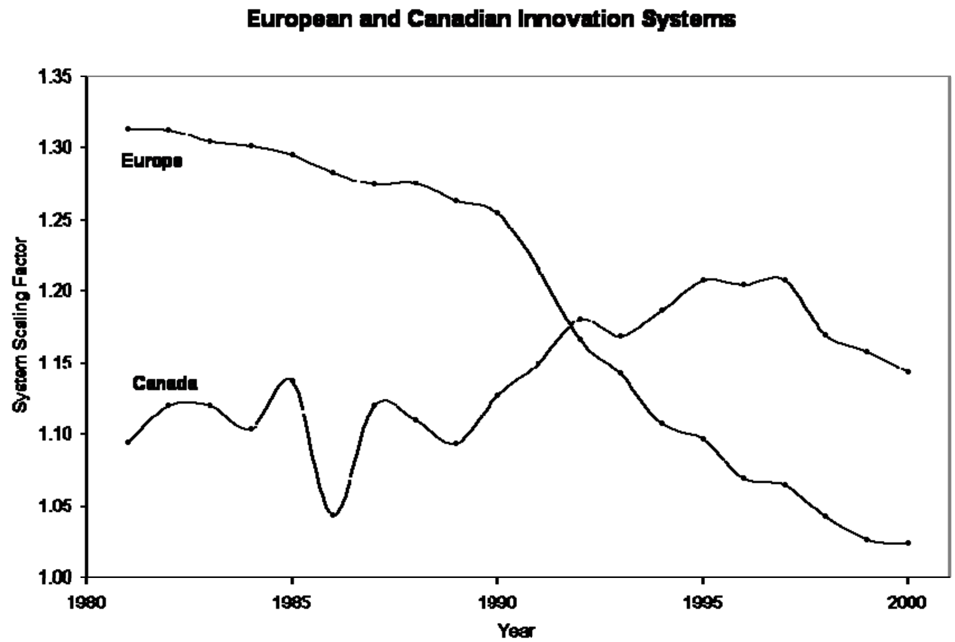


Figure 4 – Evolution of systemic GERD-GDP scaling factor with time

The systemic scaling factor for the European innovation system declined from 1.31 ± 0.19 in 1981 to 1.02 ± 0.15 in 2000. The Canadian systemic scaling factor was 1.09 ± 0.06 in 1981 and 1.14 ± 0.07 in 2000. Table 2a and Figure 2a give clues as to why the European systemic scaling factor decreased with time. The GERDs of the small and medium sized nations tended to grow significantly faster than their respective GDPs. In contrast the GERD of the larger nations like Italy, UK, France and Germany grew close to the same as or slower than their respective GDPs. The tendency was for the small and medium sized members to force the lower GDP end of the systemic scaling correlation up with time and the larger nations tended to move the upper end down or at least maintain a level close to status quo. Overall, the systemic GERD-GDP scaling factor for the European innovation system changed from being quite nonlinear (1.31) to being more linear (1.02).

In comparison the GERDs of every Canadian province grew close to or faster than their respective GDPs. The larger provinces, particularly Quebec, grew their GERDs at rates similar in magnitude to the rates of the small and medium sized European nations. It is unclear if the long term tendency of the value of the systemic GERD-GDP scaling factor for the Canada innovation system is increasing.

In summary, GERD can scale with GDP across time and at points in time. In the first instance the scaling factor is predictable and it tells us how fast GERD is growing with respect to the growth of GDP. In the second instance the systemic scaling factor is unpredictable and it tells us how GERD tends to increase with the size of member economies measured using GDP. The value of the systemic scaling factor is an emergent property that maybe useful as a measure of system activity and integration.

4. The scale-independent R&D intensity indicator

A scale-independent R&D intensity indicator is adjusted to account for the scaling correlation between GERD and GDP (Katz 2006). The measured systemic scaling correlation is used to calculate how much a member was expected to spend on R&D given the nature of the system in which it resides.

The scale-independent R&D indicator is calculated by the ratio between the *actual* amount spent on R&D and the *expected* amount calculated using the systemic scaling correlation. If a member spends more than expected the ratio is > 1, if it spends less than expected then the ratio is < 1 and if it spends the exact amount predicted then the ratio = 1. The countries and provinces above the regression line in Figure 3 had a ratio >1 and those below the line < 1. This indicator was used to rank European countries and Canadian provinces in Table 1a and 1b.

5. Scale-independent models

The rule-like scaling tendency between GERD and GDP with time was measured using a 20 year observation window. An ideal model was constructed using the scaling trends and was used to predict future values of GERD and GDP for each member country and province. In turn the future values were used to measure future values of the systemic scaling factor.

Using a 20-year and 5-year observation window the model predicted that in 2005 the European systemic scaling factors would be 0.93 ± 0.12 and 0.92 ± 0.15, respectively. The values of the system scaling factors for the Canadian innovation system were projected to be 1.22 ± 0.06 and 1.08 ± 0.09, respectively. These findings suggest that the systemic scaling factor for the European innovation system will tend to decrease and in fact the GERD is anticipated to grow slower than GDP with each doubling.

An analysis of the 2003 data showed that the systemic scaling factor for Europe was 0.94 ± 0.16 and for Canada it was 1.17 ± 0.07. As predicted the European systemic scaling factor has dipped below 1.0. The value of the systemic scaling factor for Canada is still well above 1.0 and within the range predicted by both the 20 & 5 year observation window models.

Tables 3a and 3b list the countries and provinces of the European and Canadian innovation systems[6] in descending rank order using the values of the traditional R&D intensity indicator and the scale-independent R&D intensity indicator. They are updated views of the Tables 1a and 1b

[6]ICanadian innovation system indicators: A comparison of conventional and scale-adjusted indicators from 2000-2003 is available from http://www.sussex.ac.uk/Users/sylvank/workbook/Canada%202000-2003.pdf

Table 3a - European Research Area R&D Intensity (2003)

Rank	Country	Traditional	Country	Scale-Independent
1	Netherlands	5.35	Netherlands	1.12
2	Sweden	3.91	Sweden	1.08
3	Finland	3.52	Finland	1.07
4	Denmark	2.63	Germany	1.04
5	Germany	2.52	Denmark	1.04
6	Austria	2.19	France	1.02
7	France	2.18	Austria	1.02
8	United Kingdom	1.91	United Kingdom	1.01
9	Belgium	1.86	Belgium	1.00
10	Ireland	1.16	Italy	0.96
11	Italy	1.12	Spain	0.95
12	Spain	1.06	Ireland	0.93
13	Portugal	0.83	Portugal	0.90
14	Greece	0.62	Greece	0.86

Note: Luxemburg not included allowing comparison with 1981-2000 analysis

Table 3b - Canadian R&D Intensity (2003)

Rank	Province	Traditional	Province	Scale-independent
1	Quebec	2.72	Quebec	1.60
2	Ontario	2.17	PEI	1.34
3	Nova Scotia	1.43	Nova Scotia	1.23
4	British Columbia	1.35	Ontario	1.14
5	Manitoba	1.17	Manitoba	0.97
6	PEI	1.09	Saskatchewan	0.89
7	Saskatchewan	1.07	British Columbia	0.88
8	Alberta	1.06	NFL	0.83
9	NFL	0.89	New Brunswick	0.79
10	New Brunswick	0.87	Alberta	0.67

NFL - Newfoundland and Labrador; PEI – Prince Edward Island

Note that the rank order of European countries is nearly the same for both the traditional and scale-adjusted R&D intensity indicators[7]. This is expected because the systemic scaling factor for the European innovation was measured at just below 1.0. If it were equal to 1.0, that is if GERD increased linearly with GDP, then the rank order for both methods would be precisely the same. In comparison the values of the systemic scaling factor for the Canadian innovation system is larger than 1.0. The rank orders of the Canadian provinces by the two methods differ considerably.

[7] Note Germany and Denmark & France and Austria are tied ranks using the scale-independent indicator

6. Overview and Policy Relevance

Members of an innovation system are ranked using performance indicators and this information is used to inform public policy decision makers. It has been shown that a unique type of non-linear relationship can exist between the numerator and denominator of the R&D intensity indicator. Similarly, scaling effects have been shown for the national wealth and scientific impact indicators (Katz 2005; 2006). Contrary to popular belief traditional performance indicators may not be normalized for size.

The ordered list of members of an innovation system can be quite different when ranked using the traditional R&D intensity indicator and the scale-independent R&D intensity indicator. The different rankings may affect the perceptions of decision makers particularly if they wish to know how much a member is contributing to the system given its size. Only indicators that are normalized for size can be used to answer such questions. Traditional indicators are only normalized when there is a linear correlation between the numerator and the denominator. Scale-independent indicators are always normalized. They can be used to compare groups of vastly different sizes.

Some might argue that when the scaling factor is close to 1.0 the non-linear effects can simply be ignored. Assume the scaling factor is 1.05 and we wish to compare two innovation systems where one system has a GDP ten times larger than the other system. Given a scaling factor of 1.05, we would expect the larger system to have a GERD 11.2 times ($10^{1.05}$) larger than the smaller one. In other words, the larger system would be expected to have a 12% larger GERD than if we assumed the scaling factor was 1.0 or linear. Thus small scaling factor can have a large effect.

Notable observers have shown that innovative human processes exhibit power law distributions and correlations. In the last century thousands, perhaps even tens of thousands, of research papers have been published illustrating that innovative human activities scale. Curiously, despite the prevalence of these scaling relationships almost no one uses them to inform public policy. We continue to use linear indicators to describe nonlinear complex systems.

Linear notions are still embedded in models of innovation even though over the past 50 years there have been efforts to replace them (Godin 2005). For example, in 1995 COSEPUP[8] of the US Academic Complex[9] deliberately blurred the distinction between basic and applied science and between science and technology (Marburger 2005). It contended that a complex relationship exists between them and in most instances the linear view of innovation is simplistic and misleading.

[8] The Committee on Science, Engineering, and Public Policy

[9] The US National Academy of Sciences, along with its component organizations, the National Research Council, the Institute of Medicine, and the National Academy of Engineering, and their various directorates, are often referred to as the Academy Complex.

Innovation systems are complex and they are expected to scale. Scale-independent indicators inform policy based on information about the amount members contribute to an innovation system given their sizes and the character of the system within which it resides. They provide decision makers with scale-independent policy relevant views of innovation systems that are not bounded by linear notions.

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