Ivory Tower Universities and Competitive Business Firms

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There is nowadays considerable interest on ways to quantify the dynamics of research activities, in part due to recent changes in research and development (R&D) funding. Here, we seek to quantify and analyze university research activities, and compare their growth dynamics with those of business firms. Specifically, we analyze five distinct databases, the largest of which is a National Science Foundation database of the R&D expenditures for science and engineering of 719 United States (US) universities for the 17-year period 1979–1995. We find that the distribution of growth rates displays a “universal” form that does not depend on the size of the university or on the measure of size used, and that the width of this distribution decays with size as a power law. Our findings are quantitatively similar to those independently uncovered for business firms, and consistent with the hypothesis that the growth dynamics of complex organizations may be governed by universal mechanisms.

In the study of physical systems, the scaling properties of fluctuations in the output of a system often yield information regarding the underlying processes responsible for the observed macroscopic behaviour. Here, we analyze the fluctuations in the growth rates of university research activities, using five different measures of research activity. The first measure of the size of a university’s research activities that we consider is R&D expenditures. The rationale for using R&D expenditures as a measure of research activity is that research is an expensive activity, and that the university finances with external support.

We first analyze a database containing the annual R&D expenditures for science and engineering of 719 US universities for the 17-year period 1979–1995 (\( \approx 12,000 \) data points). The expenditures are broken down by school and department. The annual growth rate of R&D expenditures is, by definition, \( g(t) \equiv \log(S(t+1)/S(t)) \), where \( S(t) \) and \( S(t+1) \) are the R&D expenditures of a given university in the years \( t \) and \( t+1 \) respectively. We expect that the statistical properties of the growth rate \( g \) depend on \( S \), since it is natural that the fluctuations in \( g \) will decrease with \( S \). Therefore, we partition the universities into groups according to the size of their R&D expenditures (Fig. 1a). Figure 1b suggests that the conditional probability density, \( p(g|S) \), has the same functional form, with different widths, for all \( S \).

We next calculate the width \( \sigma(S) \) of the distribution of growth rates as a function of \( S \). Figure 1c shows that \( \sigma(S) \) scales as a power law

\[ \sigma(S) \sim S^{-\beta}, \]  

(1)

with \( \beta = 0.25 \pm 0.05 \). In Fig. 1d, we collapse the scaled conditional probability distributions onto a single curve.

To test if these results for the dynamics of R&D expenditures are valid for other measures of research activity, we next analyze another measure of a university’s research activities, the number of papers published each year. We analyze data for the 17-year period 1981–1997 from the US University Science Indicators, which records the number of papers published by the top 112 US universities (\( \approx 1,900 \) data points). We find that the analogous Fig. 1 holds. Particularly striking is the fact that the same exponent value, \( \beta = 1/4 \), is found (Fig. 2a) and that the same functional form of \( p(g|S) \) is displayed (Fig. 2b).

Next, we consider as a measure of size the number of patents issued to a university. We “manually” retrieve from the webpages of the US Patent and Trademark Office’s database the number of patents issued to each of 106 universities each year of the 22-year period 1976–1997 (\( \approx 2,300 \) data points). We confirm that the analog of Fig. 1 holds, with the same exponent value, \( \beta = 1/4 \) (Fig. 3a), and the same functional form of \( p(g|S) \), Fig. 3b.

To test if our findings hold for different academic systems, we analyze two databases on research funding of English and Canadian universities. The same quantitative behavior is found for the distribution of growth rates and for the scaling of \( \sigma \), with the same exponent value (Fig. 2a) and the same functional form of \( p(g|S) \), Fig. 2b. Thus, the analysis of all five databases confirms that the same quantitative results hold across different measures of research activity and academic systems.

We next address the question of how to interpret our empirical results. We start with the observation that research is an expensive activity, and that the university must “offer” its research to external sources such as governmental agencies and business firms. Thus, an increase in R&D expenditures at university \( A \) and a decrease at university \( B \) implies that the funders of research increasingly choose their research from university \( A \) as opposed to university \( B \). This qualitative picture parallels the. 


competition among different business firms, so it is natural to enquire if there is quantitative support for this analogy between university research and business activities. To quantitatively test this analogy, we note that the results of Fig. 1 are remarkably similar to the results found for firms, universities, and countries. We plot in Fig. 2 the scaled conditional probabilities \( p(g|S) \) for countries, firms, and universities, and find that the distributions for the different organizations fall onto a single curve.

There is, however, one difference: For firms and countries, we find \( \beta \approx 1/6 \), while for universities, \( \beta \approx 1/4 \). We can understand this difference using a model for organization growth. In the model, each organization—university, firm, or country—is made up of units. The model assumes these units grow through an independent, Gaussian-distributed, random multiplicative process with variance \( W^2 \). Units are absorbed when they become smaller than a "minimum size", which is a function of the activity they perform. Units can also rise to new units if they grow by more than the minimum size for a new unit to form. The model predicts \( \beta = W/[2(W + D)] \), where \( D \) is the width of the distribution of minimum sizes for the units. For firms, the range of typical sizes is very broad—from small software companies to large oil and automobile firms—suggesting a large value of \( D \). On the other hand, for universities, the range of typical sizes is much narrower, suggesting a small value of \( D \) and implying a larger value of \( \beta \) than for business firms. This is indeed what we observe empirically.

Business firms are comprised of divisions and universities are made up of schools or colleges, so it is natural to consider the internal structure of these complex organizations. We next quantify how the internal structure of a university depends on its size by calculating the conditional probability density \( \rho(\xi|S) \) to find a school of size \( \xi \) in a university of size \( S \) (Fig. 2a). The model predicts that \( \rho(\xi|S) \) obeys the scaling form

\[
\rho(\xi|S) \sim S^{-\alpha} f(\xi/S^\alpha),
\]

where \( f(u) \sim u^{-\gamma} \) for \( u \ll 1 \), and \( f(u) \) decays as a stretched exponential for \( u \gg 1 \). We find \( \alpha = 0.75 \pm 0.05 \) (Fig. 2c). We test the scaling hypothesis (2) by plotting the scaled variables \( \rho(\xi|S)/S^{-\alpha} \) versus \( \xi/S^\alpha \). Figure 2c shows that all curves collapse onto a single curve, which is the scaling function \( f(u) \).

Equation (2) implies that the typical number of schools with research activities in a university of size \( S \) scales as \( S^{1-\alpha} \), while the typical size of these schools scales as \( S^\alpha \). Hence, we can calculate how \( \sigma \) depends on \( S \),

\[
\sigma(S) \sim (S^{1-\alpha})^{-1/2} W(\xi).
\]

In order to determine \( \sigma \), we first find the dependence of \( W \) on \( \xi \). Figure 2d shows that \( W \sim \xi^{-\gamma} \) with \( \gamma = 0.16 \pm 0.05 \). Substituting into (3) and remembering that the typical size of the schools is \( S^\alpha \), we obtain

\[
\sigma(S) \sim (S^{1-\alpha})^{-1/2}(S^\alpha)^{-\gamma},
\]

which leads to the testable relation

\[
\beta = \frac{1 - \alpha}{2} + \alpha \gamma.
\]

For \( \alpha \approx 3/4 \) and \( \gamma \approx 1/6 \), Eq. (4) predicts \( \beta \approx 1/4 \), in surprising agreement with our empirical estimate of \( \beta \) from the five distinct databases analyzed (Fig. 3a).

Our results are consistent with the possibility that the statistical properties of university research activities are surprisingly similar for different measures of research activity and for distinct academic systems. Moreover, our findings for university research resemble those independently found for business firms and countries. One possible explanation is that peer review, together with government oversight, may lead to an outcome similar to that induced by market forces, where the analog of peer-review quality control may be consumer evaluation, and the analog of government oversight may be product regulation.

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FIG. 1. Growth dynamics of research activities at universities. a) Histogram of the logarithm of the annual R&D expenditures of 719 US universities for the 17-year period 1979–1995, expressed in 1992 US dollars. Here, $S$ denotes the R&D expenditures detrended by inflation so that values for different years are comparable. The bins were chosen equally spaced on a logarithmic scale with bin size 0.5. The line is a Gaussian fit to the data, which is a prediction of Gibrat’s theory [10,12]. b) Conditional probability density function $p(g|S)$ of the annual growth rates $g$. For this plot the entire database is divided into three groups (depicted in (a) by different shades). c) Standard deviation $\sigma(S)$ of the distribution of annual growth rates as a function of $S$. The straight line is a power law fit to the the data, and its slope gives the exponent $\beta = 0.25 \pm 0.05$. d) Scaled probability density function $p(g(S)/\sigma^{-1}(S)$ plotted against the scaled annual growth rate $(g - \bar{g})/\sigma(S)$ for the three groups defined in (b). Note that the scaled data collapse onto a single curve.

FIG. 2. Robustness of empirical findings for the distribution of growth rates. a) Standard deviation $\sigma(S)$ of the distribution of annual growth rates for different measures of research activities and different academic systems from the data in the five distinct databases analyzed: (i) the number of papers published each year at 112 US universities, (ii) the number of patents issued each year to 106 US universities, (iii) the R&D expenditures in US dollars of 719 US universities, (iv) the total amount in Canadian dollars of the grants to 60 Canadian universities, and (v) the external incomes in British pounds of 90 English universities. It is apparent that for all measures and all academic systems analyzed, we find a power law dependence—with the same exponent $\beta \approx 1/4$. The values of $\sigma$ for the different measures were shifted vertically for better comparison of the estimates of the exponents. b) The distribution of annual growth rates, scaled as in Fig. 1d, for the five databases. We show the distribution of growth rates for 2 different groups, obtained in a way similar to that described in Fig. 1b, for each of the five measures. The data appear to collapse onto a single curve, suggesting that the different measures have similar statistical properties. c) The distribution of scaled annual growth rates for different organizations: R&D expenditures of US universities, sales of firms, and GDP of countries. The data collapse onto a single curve suggesting that the scaled distributions have the same functional form.
FIG. 3. Statistical analysis of the units forming the internal structure of a university, the schools. a) Conditional probability function $\rho(\xi|S)$ of finding a school of size $\xi$ in a university of size $S$. To improve the statistics, we partition the universities by size into four groups. b) To illustrate the scaling relation (2), we plot the scaled probability density $\rho(\xi|S)/S^{-\alpha}$ versus the scaled size of the school $\xi/S^\alpha$. In agreement with (2), we find that the scaled data fall onto a single curve. c) Scaling of the typical size of a school in a university of a given size for different university sizes. The data obey a power law with exponent $\alpha = 0.75 \pm 0.05$. d) Standard deviation $\mathcal{W}$ of the distribution of growth rates of schools versus school size $\xi$. The data obey a power law with exponent $\gamma = 0.16 \pm 0.05$. Using (4) and this value of $\gamma$, we obtain an independent estimate $\beta = 0.25 \pm 0.05$. 