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# A Statistical Physics Model of Technology Transfer

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## Abstract

A statistical physics description of company decisions has been developed in which modifications due to random behavior of the traditional economics description of a production function. are displayed. In this statistical physics description, unit production cost plays the role usually occupied by energy. The associated temperature is related to the maturity and degree of bureaucracy prevalent in the system

A partition function factor arises naturally that weights regions of high company concentration. From this partition function, analogues to free energy, statistical physics forces, entropy, and other statistical physics quantities can be defined.

In the model, the effect of technology transfer is exhibited by the conservation law describing how a change in the total production cost is related to both the change in the unit cost of production resulting from the action of the statistical physics force of technology transfer, and to the change in the entropy of the system brought about by technology transfer.

A natural explanation of a productivity paradox in which expenditures for information technology transfer can actually result in a transient increase in total production cost, arises from the relative magnitudes of the force and entropy terms in the conservation law.

## 1. Introduction

Technology transfer has been touted for many years as a cost effective means of improving company competitiveness. Several reasons have been given for this. For example, Krugman at Princeton posits that market responsive private firms are not the best source of knowledge (and by inference, new technology). Firms that innovate have a difficult time in capturing all the revenue streams that can be generated by the knowledge. This tends to cause private firms to have a disincentive for knowledge creation and sharing. In order to reduce times to market, firms are forced to look outside their own firm for intellectual property (IP) that can be licensed and incorporated into new products faster than it can be invented. Krugman posits that public institutions operate under a set of incentives that tend to foster knowledge creation and sharing. The knowledge creation in these institutions occurs outside the influence of market influence. The public goods stored in the tens of thousands of active patents sitting on the shelves of federally funded research institutions in the United States are still a large untapped source of knowledge. This occurs at a time when business environments have become hypercompetitive because of the high magnitude and velocity of interfirm rivalries [D'aveni, (1994)].

Knowledge transfer can be difficult in a time when innovations in products, services, business processes and organizational designs are creating dramatic discontinuities in product market spaces and disrupting the traditional approaches to competitive strategies and business conduct [Christensen (1997)]. New "sense and respond strategies" are emerging in managerial thinking [Bradley (1998)]. These new strategies recognize the value of industry clusters and their complex adaptive abilities to extended entrepreneurship to a global scale. IT driven industry clusters could be ideal for the "sense and respond" approaches [Bradley (1998)]. The development of new frameworks to explore the optimal use of IT in these strategies is underway. The problem of managing intellectual capital and transferring knowledge in the information age is a challenge with no precedent [Teece (1998)].

The purpose of this paper is to explore the impact of technology transfer from a systematic, quantifiable, and non-anecdotal point of view. This is done by developing a statistical physics model for company behavior. Analogues can be developed in the economic realm for conventional statistical physics parameters. For example, analogues can be developed for free energy, entropy, thermodynamic forces, partition functions, etc. In the statistical physics of company behavior, the role of energy can be played by the unit cost of production.

It is also possible to consider the analogue to the familiar conventional thermodynamics conservation law that relates changes in internal energy to work and the change in entropy. We shall see below that for technology transfer to companies, the corresponding conservation law in the economics realm relates changes in total production cost to the action of a uniquely defined statistical physics force of technology transfer and to a change in effective entropy.

This conservation law enables us to systematically describe the effects of technology transfer on a system of companies in terms of measurable parameters.

The statistical physics framework is summarized in Section 2. The conservation law for changes in the statistical physics parameters is derived in Section 3. The results for technology transfer are discussed in Section 4.

## 2. Statistical physics framework

There has been a long-term association between economics and thermodynamics. This association can be found in both neoclassical economics and modern new growth economics. Krugman [1996] points out that economics is based on physics, and one of his favorite examples is that of the thermodynamics of economics. Even systems far from economic equilibrium can be treated by (open system) thermodynamics [Thome and London (2000)].

Costanza, Perrings and Cleveland [1997] argue that two very different fields of science initially drove the development of new growth economic models: thermodynamics and biology. The interdisciplinary new growth (ecological) economic theories provide IT and knowledge transfer with a promising framework. .

According to Smith and Foley [2002] both neoclassical economics and classical thermodynamics seek to describe natural systems in terms of solutions to constrained optimization problems.

The formalism of statistical physics may be found in several good texts: in this paper we follow closely the succinct development in Feynman & Hibbs (1965).

It is straightforward to develop a thermodynamic-like statistical physics description of company behavior based on a constrained maximum likelihood approach. So as not to obscure the basic ideas, some simplifying approximations can be made:

1. The existence of different types of companies and different types of company outputs are ignored. For example, the different types of companies in a value-added chain within an industry cluster is not addressed.
2. The total production at a given location is assumed to be proportional to the number of [the same size] companies at that location.
3. The production costs are not divided up between labor, materials, and capital, but rather the results are based on a spatially-dependent single production cost per unit produced.
4. A simplified single factor scale invariant Cobb-Douglas production function is assumed, in which the production output of a company is proportional to the total cost of production.
5. Saturation and zoning effects are ignored.
6. A static situation is assumed [i.e. all time variations are ignored].

With these assumptions, the derivation of the statistical physics framework proceeds in a straightforward manner:

Begin by dividing up the landscape in and around a metropolitan area into a number of cells. For instance, each cell might consist of the land within a given zip code. Label each cell by "i", where we assume that i runs from i = 0 to some large number $N_T$

Assign to each cell a cost function C(i) that indicates the cost to produce one unit of production output.

Denote by n(i) the number of units produced in some standard length of time, [e.g. in a year] in the ith cell.

Characterize the metropolitan area and its surroundings by the total costs incurred in the same length of time,

$$C(\text{total}) = \sum C(i)n(i) \qquad [1]$$

and by the total number of units produced in that time,

$$N(\text{total}) = \sum n(i) \qquad [2]$$

where in both eqs. [1] and [2] the summation is from i = 0 to i = $N_T$.

With the foregoing assumptions, we now ask what the most likely distribution of production is over the cells, assuming that we know what the total number of units produced, N(total), is, and what the total cost of producing those units, C(total), is.

The N(total) units are produced by n(1) units in cell number 1, n(2) units in cell number 2, etc. In the standard approach of statistical physics, the probability of a given distribution n(i), i = 0, …, $N_T$, is determined by maximizing the number of ways in which the N(total) can be obtained given the distribution n(i), subject to the fact that both N(total) and C(total) are known.

The number of ways that N(total) can be arranged is N(total)! However, not all of these ways are consistent with the assumed distribution n(i). The number of ways n(i) can be arranged is n(i)! and each of these is equivalent as far as counting the number of ways that N(total) can be arranged. Thus, the total number of allowable ways that N(total) can be arranged subject to an assumed distribution n(i) is:

$$P[N(total), n(i)] = N(total)! / [\ n(1)!n(2)! \ldots n(N_T\mathbf{!]}$$
$$= N(total)! / \prod n(i)! \qquad [3]$$

where the $\prod$ in the denominator denotes the product of all the n(i)!'s. To deal with a sum rather than the product, we form

$$\ln \{P[N(total), n(i)]\} = \ln\{N(total)!\} - \sum \ln\{n(i)!\} \qquad [4]$$

Assuming that n(i) is large, Stirling's approximation can be used for the logarithm of a factorial:

$$\ln\{n!\} \Rightarrow n \ln\{n\} - n \Rightarrow n \ln\{n\} \qquad [5]$$

Thus,

$$\ln \{P[N(total), n(i)]\} \Rightarrow N(total) \ln\{N(total)\} - \sum n(i) \ln\{n(i)\} \qquad [6]$$

The most likely distribution of n(i) will be that for which ln{P[N(total), n(i)]} has a maximum, i.e. for which the derivatives d ln{P[N(total), n(i)]}/dn(i) = 0. However, we must also take into account the constraints of eqs.[1] and [2]. This can be done by introducing Lagrange multipliers $\alpha$ and $\beta$ to form

$$F(n(i)) = \ln \{P[N(total), n(i)]\} - \alpha [\ \sum n(i) - N(total)\ ] \ - \ \beta[\sum C(i)n(i) - C(total)] \qquad [7]$$

Then, on setting

$$dF(n(i)) /dn(i) = 0 \qquad [8]$$

we find as the condition for a maximum of ln {P[N(total), n(i)]} subject to the constraints of eqs. [1] and [2]:

$$- \ln\{n(i)\} - 1 - \alpha - \beta\, C(i) = 0 \qquad [9]$$

Solving eq. 91] for n(i), we find

$$n(i) = A \exp[-\beta C(i)] \quad [10]$$

where

$$A = \exp[-(1+\alpha)] \quad [11]$$

is an undetermined constant.

Equation [10] for n(i) has the familiar Maxwell-Boltzmann form of thermodynamics, and from that form we can construct several economic analogues of conventional thermodynamic quantities:

**"Energy" and "temperature"**

Thus,

C(i), the cost required to produce 1 unit in the ith cell, plays the role of an "energy" for the ith cell

$\beta$ plays the role of $1/k_B T$

Here, $k_B$ is Boltzmann's constant and T designates an effective "temperature".

The quantity $\beta$ can also be interpreted as a "bureaucratic factor" that is related to how risk-averse a particular industry sector is. Thus, a high $\beta$ sector is a very bureaucratic sector, whereas a low $\beta$ sector is less bureaucratic and less risk averse. Low $\beta$ firms have market agility advantages and might be expected to reside in areas of low firm density to minimize the cost of congestion and offset low economies of scale. In Applegate's [1996] classification of firms based on environment stability and organizational complexity. high $\beta$ firms would require the highly stable markets and would be capable of handling large amounts of complexity.

**Partition function**

Continuing with the statistical physics analogy, the constant A can be written in terms of N(total) and a " partition function"

$$Z = \sum \exp[-\beta C(i)] \quad [12]$$

Since N(total) = $\sum$ n(i), we find on substituting eqs. [10] and [11],

$$A = N(total)/Z \quad [13]$$

**Helmholtz "free energy"**

Carrying the statistical physics analogy even further, a "free energy" F can be introduced by the equation

$$\exp[-\beta F] = Z \quad [14]$$

so that

$$A = N(total) \exp[\beta F] \quad [15]$$

In terms of F, we see from eqs. [1] and [2] that

$$C(total) = -\partial Z/\partial\beta = F \exp[-\beta F] \quad [16]$$

The average value of C(i) can be expressed in terms of F:

$$\langle C(i) \rangle = \sum C(i) \exp[-\beta\{C(i) - F\}] \quad [17]$$

But we see from eq. [12] that

$$\sum C(i) \exp[-\beta C(i)] = -\partial Z / \partial\beta \quad [18]$$

and on using eq. [14] in eqs. [17] and [18], we find

$$\langle C(i) \rangle = \partial(\beta F) / \partial\beta \quad [19]$$

**Entropy**

It is also possible to define an entropy

$$S = -\,\partial F / \partial T = k_B \beta^2 \partial F/\partial \beta \qquad [20]$$

where the last equality arises from the relation $\beta = 1/ k_B T$. In terms of S, we can write

$$\langle C(i)\rangle = F + TS \qquad [21]$$

**“Forces”**

Finally, suppose that by varying some parameter $\xi$, it is possible to change C(i). Designate the rate of change of C(i) with respect by $\xi$ by $\partial C(i)/\partial \xi$ . Then a “force” can be defined by weighting $\partial C(i)/\partial \xi$ by the occupancy of the ith cell:

$$f(\xi) = \sum \partial C(i)/\partial \xi \exp[-\beta C(i)]/Z \qquad [22]$$

This can in turn be written

$$f(\xi) = -\,(1/\beta)\partial\{\ln Z\}/\partial \xi \qquad [23]$$

i.e.

$$f(\xi) = \partial F/\partial \xi \qquad [24]$$

For example, suppose that $\xi$ is a measure of technology transfer. Then eq. [24] defines a “force” that acts on the system associated with technology transfer. This will be explored more in the next Section.

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The correspondences between the foregoing company behavior statistical physics quantities and the familiar statistical physics parameters in conventional thermodynamics is summarized in Table 1 below.

**Table 1. Comparison of Statistical Quantities in Physics and in Companies**

| Variable | Physics | Companies |
|---|---|---|
| State (i) | Hamiltonian eigenfunction | Production site |
| Energy | Hamiltonian eigenvalue $E_i$ | Unit production cost $C_i$ |
| Partition function Z | $\sum \exp[-(1/k_B T)E_i]$ | $\sum \exp[-\beta C_i]$ |

| | | |
|---|---|---|
| Free energy F | $k_B T \ln Z$ | $(1/\beta) \ln Z$ |
| Generalized force $f_\xi$ | $\partial F/\partial \xi$ | $\partial F/\partial \xi$ |
| Example | Pressure | Technology |
| Example | Electric field x charge | Knowledge |
| Entropy (randomness) | $- \partial F / \partial T$ | $k_B \beta^2 \partial F/\partial \beta$ |

In the next Section, we shall examine relations between changes in the thermodynamic quantities to see how technology transfer can affect the total production output.

### 3. Conservation law for changes in statistical physics parameters

In conventional statistical physics, changes in the total energy of a system are related to work done by the system on its surroundings and to the change in the entropy of the system. Thus, denoting by U the total internal energy of the system, and by $S = - \partial F / \partial T$ the system's entropy, we have the conservation law:

$$dU = TdS - \langle f_\xi \rangle d\xi \qquad [25]$$

where $\langle f_\xi \rangle$ is the average over all the sites of the system of the statistical physics force $f_\xi$.

The second term represents the work done by the system on its surroundings. For example, when the force $\langle f_\xi \rangle$ is the pressure P, and $\xi$ is the volume V, eq. [25] becomes the familiar conservation law

$$dU = TdS - PdV \qquad [26]$$

To derive the corresponding conservation law for the statistical physics of company behavior, start with the expression for the total production cost C of a system:

$$C = \sum C(i)n(i) \qquad [27]$$

From the equations developed in Section 2, this can be written

$$C = \sum C(i) \exp [-\beta(C(i) - F)] \qquad [28]$$

Now consider a change $d\xi$ in a parameter $\xi$ in the system, keeping the temperature (and therefore $\beta$) constant. [For example, $\xi$ can denote the technology used in the system, so that $d\xi$ represents technology transferred to the system.] Then, in general, eq. [28] shows that there will be a change in total production costs dC due to corresponding changes in C(i) and F.

$$d_\xi C = \Sigma\, d_\xi C(i) \exp[-\beta(C(i) - F)] + \beta d_\xi F \sum C(i) \exp[-\beta(C(i) - F)] - \beta\, \Sigma\, C(i)\, d_\xi C(i) \exp[-\beta(C(i) - F)] \qquad [29]$$

In this equation, we have designated the change in C due to the change in the parameter $\xi$ with $\beta$ constant specifically with a subscript $\xi$ on the differential.

The first term on the right hand side is simply $- \langle f_\xi \rangle d\xi$ . This represents the work done by the system with the average force $\langle f_\xi \rangle$.

From the relations developed in Section 2, the second two terms on the right hand side of eq. [29] can be written

$$\beta d_\xi F \sum C(i) \exp[-\beta(C(i) - F)] - \beta\, \Sigma\, C(i)\, d_\xi C(i) \exp[-\beta(C(i) - F)] = \beta\, [\partial^2 F / \partial\beta\partial\xi]\, d\xi \qquad [30]$$

i.e. eq. [29] can be rewritten as

$$d_\xi C = - \langle f_\xi \rangle d\xi + \beta\, [\partial^2 F / \partial\beta\partial\xi]\, d\xi \qquad [31]$$

Equation [31] gives the change in the system's total production costs due to a change in the parameter $\xi$ when $\beta$ is held constant.

In general, when the system is in contact with another system [e.g. one from which it expects to reap the benefits of technology transfer], the temperature (and $\beta$) of the system can also change. Accordingly, the total change in the production cost C is

$$dC = d_\xi C + d_\beta C \qquad [32]$$

where the second term in this expression denotes the change in C due to a change in $\beta$ without a change in $\xi$. Specifically, since we can write from the relations derived in Section 2,

$$C = \partial\, [\beta F] / \partial\beta \qquad [33]$$

$$d_\beta C = [\partial^2[\beta F]/ \partial\beta^2]\, d\beta \qquad [34]$$

On combining eqs. [31]-[34] we find for the total change in production costs

$$dC = - \langle f_\xi \rangle d\xi + \beta\, [\partial^2 F/ \partial\beta\partial\xi]\, d\xi + [\partial^2[\beta F]/ \partial\beta^2]\, d\beta \qquad [35]$$

Equation [35] is the desired conservation equation corresponding to eq. [25] for conventional statistical physics. The first term on the right hand side describes the "work" done by the system and the second term represents the "heat" exchange associated with a change in the system's entropy. Indeed, using the relations summarized in Table 1, eq. [35] for the statistical physics of company behavior may be rewritten in the same form as eq. [25}:

$$dC = - \langle f_\xi \rangle d\xi + TdS \qquad [36]$$

## 4. Implications for technology transfer

In terms of the statistical physics model developed in Section 2 and the conservation law derived in Section 3, there are two basic ways in which knowledge transfer and information technology can impact overall production costs:

### 4a. Reduction in unit cost of production

The first is the familiar possible reduction in unit production costs [the first term in the conservation relation of eq. (36)]. If the new technology does indeed reduce the unit cost of production, then the first term in the conservation equation is negative. The term by itself would then contribute to a decrease in total production costs.

It is possible, on the other hand, that the transfer of new technology to a company can increase the unit cost of production. Hopefully, this would be a transient effect. But the initial investment in transferring and incorporating the new technology in production lines could indeed result in a transient productivity paradox in which the total cost of production is impacted in just the opposite way to that desired.

### 4b. Change in system entropy

The second way in which technology transfer can impact total production costs is in the change it can introduce into a system's entropy. The second term in the conservation equation, eq. [36], describes the consequences of heat flow into and out of the system.

In a strict heat flow analogy, if the system's temperature (degree of randomness) is larger than that of the surroundings from which it is hoping to transfer technology, then contact with the sources of technology might be expected to lower the temperature of the system

– i.e. to decrease the entropy of the system. This would then contribute to a lower overall production cost for the system. On the other hand, if the technology sources have a higher temperature than the system of interest, then technology transfer could in fact increase the temperature: the entropy term would then tend to increase overall production costs. Whether or not it would is determined by the relative magnitudes of the two terms in the conservation relation – i.e. on whether an increase in system temperature is large enough to overcome the hoped-for reduction in unit production costs.

It is not clear how valid a strict interpretation of "heat flow" in the thermodynamics of company behavior is. A priori, it is difficult to relate the parameter $\beta$ to technology transfer, except to say that introduction of new technologies does have a "noise" aspect to it, in that old systems are disrupted. Thus, it might be expected that the effective temperature for young companies is larger than for mature, well established companies, and that the temperature is higher for companies based on newer transferred technology rather than on older technologies.

As an example, it was found in comparing the temperatures of the semiconductor sector in the four counties comprising the Los Angeles consolidated metropolitan statistical area for the years 1992 and 1997, that the temperature actually decreased as time progressed. Expenditures for information and new technology in this sector were relatively high in the period between the two data samples. It appeared that the temperature actually decreased as the industry matured.

## 5. Conclusion

The statistical physics approach of this paper provides a systematic framework for analyzing the effects of technology transfer. The two effects identified make intuitive sense: on the one hand, technology transfer can lower the unit costs of production, and on the other hand, technology transfer can cause a broader distribution of unit production costs. It is interesting that the formalism shows that the two effects can have opposite consequences for the overall cost of production in a sector, and that this might a cause of the productivity paradox that has been cited often in theliterature.

It is clear that much more can be done with the statistical physics model of company behavior. It will be interesting to apply it as a framework for analyzing the effectiveness of past government technology transfer programs, since it does provide quantifiable measures in both the cost and entropic realms.

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