Multisectoral Growth and National Innovation Systems

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Because of their emphasis on bounded rationality and on technology as a very special kind of good, many economists dealing with the economics of technical change and the broader field of evolutionary economics tend to apply a form of theorising that de-emphasise formal abstraction and the related modelling criteria of rigour, consistency and robustness (see e.g. Dosi et al. 1988, Freeman and Soete 1997). Instead they emphasise relevance for description and policy-making in relation to the real world. The term used by Nelson and Winter (1982, 46) for this style of research is "appreciative theorising".

For ambitious researchers, like e.g. Nelson and Winter, this style of research is not an attempt to avoid formal modelling per se. For them it is often the only way of theorising about important economic phenomena, given the gap between these phenomena and the scope of available formal modelling tools. There is, however, an inherent contradiction in ambitious appreciative theorising: it tries with rather simple and informal means to capture phenomena that are more complex that the ones treated by mainstream modelling tools. This is especially obvious in the recent studies on hyper-complex phenomena like national innovation systems and technology systems. Such studies started with e.g. papers by Freeman (1988), Lundvall (1988) and Nelson (1988). Now we see many national studies, intensified descriptive work by international organisations as well as collective works edited by e.g. Lundvall (1992), Nelson (1993), Carlsson (1995) and Edquist (1997).

In relation to this new wave of innovation systems studies there is a need of a new type of model which is on the one hand open to the issues confronted by appreciative-style researchers and on the other hand able to capture systematically the core interdependencies of an economic system with heterogeneous firms engaged in exploring and exploiting an expanding set of economic activities. The paper outlines a type of model which is designed for this purpose. To begin with it is, however, useful to consider the debate on appreciative theorising.

Appreciative and formal theorising

Appreciative theorising is good for exploring a new problem area and for establishing a preliminary agenda for empirical and conceptual research. But in a certain sense appreciative theorising is too flexible when confronted with the huge number of ways of reducing the complex phenomenon of an innovation system into a manageable form: it does not constrain each researcher from choosing an idiosyncratic specification. This problem becomes obvious if a research area like that of innovation systems grows both in terms of number of researchers and diversity of their approaches. Then is becomes obvious that there is a need for a common language—a kind of *lingua franca*. This language will not only help communication between the researchers in the area but also provide a standardised interface towards economists in general, producers of innovation statistics and policy makers. The normal way of providing such a language is to construct a simple formal model and make it known to all members of the research community as well as to many outsiders. When communicating about more advanced results, researchers start from the commonly known model and tell how it should be modified to include the new results. Without the shared model the researchers would have to start their communication from scratch each and every time.

The very success of appreciative theorists brings them back to the problem they originally tried to transcend: the inadequacy of available tools of formal modelling. But at the same time their rich set of theories about their problem area makes it very difficult for them to select a particular simplification as a candidate for a foundational formal model. Therefore, it is often outsiders rather than insiders who suggests possible core models. At the moment it is especially some of the contributors to new growth theory and new trade theory who point towards a change in the situation.

Suggestions from outsiders

According to researchers like Romer and Krugman appreciative theorists are fighting a loosing battle. In this respect these theorists look like the main contributors to "high development theory" in the 1940s and 1950s (Rosenstein-Rodan 1943, Myrdal 1971, Hirschman 1961) who apparently faced the same problem and choose the same solution: to stick to the not-too-formalised version of their theory (cf. Romer 1993a, Krugman 1995). According to Romer (1993a, 553 ff.) the appreciative theorists in the economics of technical change and evolutionary economics (like Nelson and Winter 1982, Dosi et al. 1990, Dosi and Freeman 1992) should not ignore the destiny of the development economists: "If this work continues to operate in isolation from the formal modelling traditions of mainstream economics, it too may be lost and ignored."

Romer is, however, quick to point out that the present-day situation has new possibilities for theorists who emphasise empirically oriented modelling and untraditional visions. This new setting is not least created by the successes of new growth and trade theory due to the inclusion of increasing returns, spillovers and imperfect competition into mainstream models. Especially the "second-round or 'neo-Schumpeterian' models of growth with monopoly power", like the models of Romer (1990) and Grossman and Helpman (1990), "may help to bridge part of the gap between the mainstream theorists and appreciative theorists" (Romer 1993a, 556) On this background (Romer 1993a, 569) concludes with the suggestion of "a natural division of labour in future research" where mainstream theory tries to include more and more elements in "simple abstract models" while the outsiders (like Rosenberg 1976, Fagerberg 1987, David 1991, Mokyr 1990, Nelson 1993) "push the kind of evidence that they have collected" towards aggregative statistical analysis and in-depth case studies. This work includes the further development of the "studies of national innovation systems in a variety of industrial and newly industrializing countries". (Romer 1993a, 561)

Insider reactions

Romer's analysis of the situation of appreciative theorists, econometricians and historians in the Nelson and Winter tradition (and similar traditions) is surprisingly precise. But he tends to de-emphasise their need for a process of formalisation and simplification of theories and computer models which is much closer to their traditions than new growth theory is likely to come for a long time. Such an effort is helped by the possibilities of an interaction with the works of the new growth theorists, but Romer obviously overestimate the contribution that comes from new growth theory.

This point has recently been strongly emphasised by Nelson (1994, 1997). To him new growth theory is only new in formal modelling terms and its basic heuristic—that growth theory must conform to general equilibrium models—is highly constraining. To be more specific, new growth theory seems finally to have catched up with parts of the set of empirically oriented propositions which have for a very long time—at least since

Abramovitz's (1952) early survey—been related to growth theory. These propositions have been substantiated and expanded by a large amount of empirical research and appreciative theorising. But in this respect the contribution of the formal theory of Romer, Grossman, Helpman and others is very selective: only the easiest part of the basic propositions of the process of endogenous technological change has been taken into account in the highly constraining framework of general equilibrium under monopolistic competition. What is still missing in the formal models is not least

- "that technological advances today are significantly shaped by what has (and has not) been achieved earlier" (Nelson 1997, 50),
- "that issues of firm organization and strategy is at least as important to technical advance as the quantity of their investment in research and development" (Nelson 1997, 50),
- "that national institutions are important for supporting the technological and organizational capabilities of business firms." (Nelson 1997, 52)

These sketchy suggestions are, of course, expanded in Nelson's (1994, 1997) articles, but still he is very unspecific about the kind of formal model that would be a satisfactory reflection of important parts of the state of the art of evolutionary theorising about economic growth and development (surveyed by e.g. Dosi 1988, Nelson 1995). The suggestions are simply too open-ended to function as "demand specifications" from the users to the suppliers of formal models. A paper co-authored by Nelson and Romer (1996) about types of science-technology interaction does not help to change the situation.

Intermediate modelling

To promote the formal treatment of the appreciative theorists' results about systems of technologies, firms and institutions, there is an obvious possibility of using the tradition of "heterodox" formal modelling and computer simulation that relates to Nelson and Winter (1982). However, this tradition (see Silverberg and Verspagen 1997) seems hitherto to have had limited success in creating a framework that can easily be used to sum up the results of much of appreciative theorising. It is, for instance, telling that

Nelson's (1992) and Nelson and Rosenberg's (1993) summaries and evaluations of a comparative survey over about 15 national innovation systems do not refer to the Nelson and Winter tradition of modelling and simulation. It seems that this tradition does not yet live up to Nelson's requests to formal models.

The present paper suggests a new type of evolutionary models that may become a middle ground between the different types of theorising. It is based on the feeling that there is some very basic work to be done: to clarify the concept on innovation systems and related concepts; to suggest a simplistic growth model in which these concepts make sense; to enhance the understanding of the concepts in relation to an analysis of the transformation of innovation systems in relation to changes in the underlying economic system.

I think it is possible to be more specific than Nelson's above-mentioned requirements. In a middle-ground model

- technology must be sufficiently complicated to allow for continually emerging choices of specialisation of production and R&D,
- firms must have a sufficiently complex inner structure and a memory of some production techniques that are not in use all the times to allow for cumulativeness in a multitechnology space of specialisation,
- there must be interesting co-ordination problems relating to technological development that might be solved by (national) institutions.

These points emphasise that the models of Nelson and Winter (1982) are not candidates for a solution. In their family of models of "Schumpeterian competition" firms make innovative and imitative R&D in order to improve their single Leontief-type productivity used in the production of a single homogeneous product. It is, however, possible to develop an adequate model family which is—distantly—related to the Nelson and Winter models. In this type of model firms are engaged in the production of an increasing set of products, and they are able to improve their productivity with respect to all these products. Each firm has to decide which products they will specialise in and they also have a specialisation strategy with respect to R&D.

Apart from its Nelson and Winter background this new type of model (sketched out in Andersen 1996, 1997a, 1997b) has additional purposes and backgrounds (including a relationship to endogenous growth theory). It can, however, most easily be understood as an attempt to provide an evolutionary economic micro foundation to Pasinetti's (1981, 1993) scheme of the structural economic dynamics of a pure labour economy.

This relationship builds on common purposes of both Pasinetti's and the present modelling scheme. The primary goal of both type of model is to bring out clearly one of the best documented empirical regularities of economic growth: that long-term growth is always related to major changes in the composition of the economic system. The two types of model also take serious another, somewhat more disputed, stylised fact, namely that increased diversity of the economic system is an integral part of long-term economic growth.

Within this setting the models give a simple representation of an important problem for the innovation system of an economy: innovative activities with respect to the presently produced goods creates the preconditions for long-term growth but without an engagement in new sectors, the growth potential will not be exploited because of the long-term satiation of demand within the given sectoral framework. But the evolutionary type of model with an explicit representation of the problems of heterogeneous firms can proceed in specifying the problems of innovation systems. Actually, it is the basic proposition of the paper that it may lead the way towards a relatively extensive theory of innovation systems.

The evolutionary model

The model depicts economic systems based on barter trade in which each firm in principle competes with all other firms in all areas of production. In other words, each firm has a—normally primitive—potential for producing any good. Thus the firm can be self-sufficient in the sense that it can take care of the—primitive—consumption needs of its employees. Each firm has also the capability of improving its knowledge about the production of all goods. However, if a firm spreads its creation of knowledge over a wide range of goods, all its unit labour costs will stay high. This pattern of knowledge creation is problematic when there is a potential for wide-spread exchange of goods. To exchange goods is only rational if this exchange exploit a heterogeneity of firms with respect to productive knowledge about different areas of production. To develop and uphold a pattern of productive knowledge that gives large advantages from barter trade is a major challenge both for individual firms and for the system of firms. To explore this challenge is the main problem underlying the design of the model.

Firms and countries

The only explicit agents of the model are "firms" that organise the production and consumption of their fixed labour force. In other words, we are dealing with "consumer-producer firms". To establish a rapid intuition about consumer-producer firms, the reader may think of firms in an economic system where very-long-term labour contracts have come to dominate, but there are several alternative interpretations. One possibility is that firms are consumer-producer co-operatives, another that we are facing consumer-producer households of the peasant and artisan type.

The only goal of firms is to maximise the utility of their "members". This goal is obtained by producing and exchanging a variable range of consumption goods. These goods are distributed equally between the members.

The firms are attached to a single country. Countries have only a role to play when it comes to the reduction of transaction costs and the organisation of technological change. Without any loss of generality we shall normally deal with two countries: the home country and the foreign country. When it is necessary to distinguish between the two countries, the variables related to the foreign country are marked with an asterix. For instance, G_t^* is the average standard of living in the foreign country in period t.

Consumption and utility

Consumption may include any of an open-ended array of goods. For each good there is a maximum level of per capita consumption common to all countries. Goods are placed in a hierarchy so that consumers prefer to consume a lower-level good up to its maximum before a higher-level good is consumed. The goods have the indexes $1,2,\ldots,i,\ldots,$ and the index numbers of goods reflects their place in the consumption hierarchy.

If there are no "holes" in the sequence of consumed goods, the utility index, G_{jt}, is simply the number of goods consumed up to their maximum. If e.g. $G_{jt} = 5.64$, it means that the employee-owners of firm *j* in period *t* have maximum consumption of the first 5 goods while they consume 64% of the maximum of the 5th good. Goods that—due to decision-making problems in a complex exchange system—come after a "holes" in the ordinary sequence of consumption increase the utility index less that fully hierarchically consumed goods.

Production

The economy is endowed with only one factor of production, labour, which is provided by the employees of firms. There is a fixed number of individuals, and each of them supplies a fixed amount of labour. There is no labour market, so employees are distributed permanently between the firms. For simplicity we shall assume that all firms have the same number of employees or "members".

Labour can be used to produce any of the goods in the consumption hierarchy as well as for R&D. Each firm has a specific labour productivity for each good, and these productivities are independent of the size of production. If firm *j* spends one unit of labour on good *i*, it produces A_{ijt} units this good. If it spends L_{ijt} units of labour, it produces $Q_{ijt} = A_{ijt}L_{ijt}$. The firm's open-ended list of labour coefficients $\left(A_{1jt},\ldots,A_{ijt},\ldots\right)$ reflects its private set of production algorithms. The algorithms can be improved by R&D. Algorithms that has not been improved beyond the basic level of knowledge, have very low productivities.

The labour coefficient $\left(A_{ijt}\right)$ for the production of a particular product is determined by the firm's activity-specific knowledge. This knowledge is represented by an algorithm for the production of each good. Each algorithm consists of a series of *M* steps which we sometimes want to specify in terms of the productivities of the individual steps. If all steps are of equal weight, we have $A_{ijt} = \sum_{k=1}^{M} A_{ijkt}$. In each period the firm produces with constant returns to scale in all processes and subprocesses.

Bilateral exchange

Firms may engage in bilateral exchange and thus exploit comparative advantages. But there is a minimum level of productivity differentials that is necessary if firms are to engage in exchange. The reason is that there are transaction costs. These costs are modelled so that the receiving firm obtains only a fraction of the quantity delivered by the supplying firm (the "iceberg" model). The costs of each exchange depend on the location of the two involved firms, so we discern between intercountry and intracountry transaction costs. Large intercountry costs lead country-level autarky, but even within a country the transaction costs may be so high that the result is firm-level autarky. Other constraints on exchange are that stocks of goods cannot be stored from one period to the next and that a firm cannot be both a buyer and a seller of the same good in the same period.

Exchange is based on contracts related to order production. The system of contract making can be organised in a great many ways. In the model the solution is to let the market process runs successively through the hierarchy of goods, starting with good 1. For each good i, firms enter one by one according to their relative performance. When its turn comes, a firm tries to make as many profitable contracts as possible with itself as the supplier of good i. It starts by asking for trade partners that can supply it with its weakest-productivity good, l. The potential trading partners enter according to their relative performance with respect to good l. If an exchange is possible and profitable for both parties, a contract is made. The exchange rate between the two goods depends on the relative productive strength of the two parties.

This organisation of exchange—without a system of money and prices—is designed for experimental economies with relatively few firms and goods. From a computational point of view such an economy is very inefficient. This is demonstrated by the fact that simulation time increases exponentially with the number of firms and goods. But the bilateral-exchange system has many advantages in relation to the bottom-up construction of a simple economic system.

R&D investment

Each firm has an R&D intensity rule that tells it in each period to spend a certain fraction of its labour on R&D. This R&D falls in two parts that are motivated by two outcomes:

process innovation and product innovation. Product innovation concerns the finding of designs of goods. These designs are the precondition for producing the goods. Thus, the improvement of the algorithm for producing a good by means of process innovation has no meaning before the design is found. However, many the problems of the division of the creation of knowledge can be explored even if—as we shall sometimes do—the model is simplified to take into account only process innovation (by assuming that product designs are freely available).

As a result of the firm's R&D work in period *t*, a better algorithm for activity *i* may be found. Whether an innovation will actually take place is determined in four steps. First, we find out how many (if any) innovations that is obtained by the firm in period *t*. This is determined by a probability function which depends on the firm's R&D effort. Second, we see which of the algorithms are subject to innovation. This is determined probabilistically by means of the "focusing function" that reflects the way the firm specialises its R&D work. Third, we find a new potential labour productivity. Normally it is assumed that technological development is cumulative so that we find the (log of the) new productivity in a probability distribution which has the (log of the) existing productivity as its mean. But it is also possible to define technological progress functions with an exogenous, science-based mean and with general or country-specific spillovers between firms. Fourth, the firm implements the innovation in the next period if it is better that the previous algorithm, i.e. if $A_{ij,t+1} > A_{ijt}$.

The second step in the determination of the outcome of R&D—the application of the focussing strategy—is new compared not only to Nelson and Winter (1982) and Winter (1984) but also to multisectoral models of endogenous growth like the ones of Aghion and Howitt (1998). Given the complexity of the present model, this strategy of how to focus the attention of its R&D work to a subset of the hierarchy of goods has to be formulated as a "rule of thumb", and firms will differ with respect to the adequacy of their rule under given conditions. However, some rules are obviously better than others.

Since the hierarchy of goods is infinite, it is obviously non-sensical to focus with equal weight on all possible goods. The (boundedly) optimal strategy in a state of autarky of firms is, in the main, to focus attention in proportion to the amount of labour spend on the production of a particular good. When exchange is introduced, this strategy can also be applied. But with highly developed exchange, firms will obviously have to focus on improving production of a single good or a few goods.

To produce a particular good the firm needs to obtain knowledge of an appropriate product design. The method for finding such designs is nearly equal to the method of process innovation. The issue of an adequate focusing strategy is even more important in the case of product innovation than in the case of process innovation: the inability to find a product design for the next good in the hierarchy of goods can effectively block growth in the model. When a firm has found a new design, other firms can imitate the design at low costs—unless a design-oriented patent system has been introduced.

The innovation system

The concept of innovation systems is useful for specifying both the R&D strategy of the firm and the outcome of its innovative activities in a multisectoral setting. The concept of innovation system has normally been developed in a top-down manner from the economy level to the firm level. But the present model allows a complementary analysis in the bottom-up style. To develop this style we shall start from the concept of a firm-level innovation system (a corporate innovation system) which for each firm is characterised by its allocation of innovative labour across the different areas of process and product innovation as well as by the interaction of these activities with each other and with the innovative activities of other firms (and the public sector) in the determination of the probability of and distribution of innovations and imitations.

In the simplest case we can hardly talk of an innovation system in the strict sense since the activities in other areas and other firms have only a very weak influence on the probability of the innovative success of a particular firm in a particular area: the dominant influence comes from its own innovative activities within that particular area. Even in this simple case the activities of other firms have a strong influence on the profitability of a firm's innovative activities. If all firms make innovations with respect to one or a few goods, then the individual firm will have less motivation for doing R&D than if the firm has a speciality which is less frequently innovated by other firms. Thus we may in a looser sense talk of a less specialised and a more specialised "innovation system".

From a system-level viewpoint both innovation systems in the loose sense and the strict sense are of great interest. As pointed out above a major issue is how the overall innovation system copes with innovation in new products when facing satiation of demand in old products. Other issues relate to the problem of how a firm can specialise its knowledge creation when it is confronted with the danger that innovations of other firms may drive the firm out of business and thus the consumption level of its members back to the autarky level—which is very low because no effort has been made to secure a broad set of competencies.

Explorative experiments

The design of the evolutionary model of growth and specialisation is obviously not made for allowing immediate formal analysis—although it can be compared with some multisectoral growth models (especially Yang and Ng 1993). No attempt will be made to emphasise these possibilities. On the contrary, there is a danger that a premature simplification of the model needed for emphasising the relationship with formal growth modelling may as a side-effect have a break-down of bridge between appreciative theorising and the present model. The first priority for the development of the present "intermediate model" is to enter into dialogue with appreciative-type theorists by exploring the model through simple thought experiments and computer simulations (cf. Andersen 1997a and 1997b, as well as the tools in Andersen et al. 1996). Such experiments explore how growth in individual and average standard of living (G_{jt} and G_t) is influenced by the introduction of intracountry and intercountry exchange as well as by different focusing strategies and innovation systems.

The basic set-up

The basic story underlying a large class of experiments is that we have two countries, a weaker home country and a stronger foreign country (the latter's variables and parameters are marked with an asterix). These countries are compared a three points of time. At time $t = 0$ we start the experiment with initial conditions. Then we at time $t = \tau$ change the behaviour of the firms in one or both countries. Finally, we observe the standard of living obtained in the two countries at time $t = T$. The home country is at least weak with respect to its start-up conditions and behavioural rules. The weakness may be reflected in relatively high transaction costs, relatively low R&D intensity, or relatively inadequate focussing strategies. In the beginning of the second period some change in the basic conditions is made in order to improve the situation of the home country. The problem is then if and to what extent the home country at the end of the second period has improved its absolute and relative standard of living.

To simplify the comparisons we shall assume that each country has the same number of firms, $N = N^*$, and that each firm has one employee. All firms allocate their labour endowment so that $1 - r_{jt}$ units of labour are used for productive activities and r_{jt} units of labour are used for R&D. The production labour is allocated in order to maximise the standard of living, given the maximum per capita consumption of any good, $C_i = 1$. The initial level of generic knowledge is so that all goods can be produced with a productivity, $A_{ij0} \geq 1$. This means that by applying generic technology each firm can produce 1 good up to its maximum or, in other words, the standard of living of the members of firm *j* in the home country is $G_{j0} = 1 - r_{j0}$. For simplicity we shall normally assume that the initial level of generic knowledge does not change over time, although it is easy to include a spillover from good-specific R&D to generic knowledge in the style of endogenous growth theory.

It is helpful to start the experiments from a situation with no exchange and then let the two economies evolve in a bottom-up manner. This situation can be obtained if all firms in both countries at $t = 0$ have only access to unimproved generic knowledge. Given this assumption, we have initially both intercountry autarky and intracountry autarky. The background for this situation can e.g. be that there has been no R&D before start-up.

To get things moving we shall assume that both countries in the initial period start to engage in R&D—normally with different intensities and/or focussing strategies. The appropriability conditions are at present so that there are no spillovers of product designs between countries and no spillovers of process algorithms between firms. At present we shall also assume that intracountry transaction costs are small but that intercountry transaction costs are prohibitive for any intercountry exchange.

Enforced and anticipatory product innovation

The behavioural rules of the two countries are different. The firms of the home country have a learning-by-doing-like strategy according to which R&D activities are distributed over production activities in proportion to their employment. The home country firms are also reluctant to engage in product innovation since product designs, once they are made, are freely available to the other home country firms. This means that in the initial situation all their R&D is focussed on the improvement of the algorithms for the production of good 1. The firms of the foreign country have a looser relationship between production and R&D. This means that R&D efforts are likely to be spread more evenly over existing goods than the distribution of production employment would suggest, although there is some relationship. Furthermore, the firms of the foreign country follows a more anticipatory strategy that tells them to use a significant fraction of their R&D on the next good in the hierarchy, i.e. good 2.

The different focussing strategies of the two countries imply different growth performance. When the level of productivity of firms in the foreign country allow then to produce more than the maximum level of good 1, they can often immediately take up production of good 2, while the firms of the home country will have a kind of "technological underemployment" while they are searching for the design of good 2 and thus the possibility of producing it. In other words, the firms of the home country have in the end to ignore the public good character and the free-rider problem of product designs. On the other hand, the firms of the foreign country dislike idleness even more than free riders. These differences repeats themselves each time the consumption the highest goods has reached its maximum level. Since the arrival rate of new product designs is modelled as a Poisson process, the home country has on average to wait a period which depends on the R&D in the home country.

From autarky to intracountry exchange

Given the differences in standard of living between the two countries are likely to be reinforced by the emergence of bilateral exchange. As soon as production in the foreign country covers more than one good, there is a chance of exploiting productivity differences between firms. Due to the probabilistic and cumulative character of process innovation, some firms will become better in producing good 1 and some will become better in producing good 2. However, the productivity differentials have to be sufficient to overcome the problem of transaction costs. A firm j^* that specialises in good 1 will have to pay the full labour costs of producing a surplus which it would like to exchange with another firm k^*. But in return it does not get the full quantity of good 2 produced by firm k^*. Transaction costs functions as if a certain fraction of good 2 disappears on its way from firm j^* to firm k^*. Although this effect functions symmetrically, the result it that significant productivity differentials are needed.

Such differentials are likely to emerge fairly easily in the case of foreign country firms with their arms-length relationship between production and R&D. However, the situation is somewhat different in the home country. Here R&D is distributed in proportion to production employment. This means that R&D concentrates of equalising the productivities in the different areas of production. Let us, for instance, take the case where two home country firms are waiting to become able to start production of good 3. In the meantime they consider exchanging the first two goods. Firm *j* is best in producing good 1 and firm *k* has its advantage in good 2. This situation is, however, likely to become less clear. So if the productivity differentials are not sufficient to allow exchange, they are even less likely to become so in the future. The reason is that for its in-house consumption firm *j* employs more labour for producing good 2 than good 1. As a consequence its R&D is more likely to improve the algorithm for good 2 than for good 1. Since the opposite situation is found in firm *k*, R&D serves to diminish productivity differentials. This is an adequate strategy for dealing with production for in-house use but it slows down the emergence of exchange.

The relative difficulties of the emergence of exchange in the home country compared to the foreign country, together with its difficulties in product innovation, gives strong reason to believe that the home country has a relatively weak growth performance. However, the home country may show some spontaneous recovery. The reason it that its R&D strategy can promote a relatively stable specialisation of its firms—once exchange takes off due to random—and rather seldom—emergence of productivity differentials that are sufficient to allow for trade. When firm *j* specialises in good *i*, its employment with respect to that good will also increase and so will the good-specific R&D effort. However, in a more turbulent R&D regime where other firms are likely to take over the delivery of good *j*, such a specialisation may create problems. If firm *k* is forced to return to autarky, all its R&D efforts with respect to good *i* will—at least for a period—become irrelevant if $G_{jt} < i$.

From intracountry to intercountry exchange

The above discussion of the evolution of the system of firms in each of the two countries, we can summarise the situation at time $t = \tau$. The range of goods produced by the foreign country is larger than the range of the home country. Similarly the standard of living is larger abroad than at home. Concerning the variance of productivities within the range of production, it is more difficult to give a clear-cut conclusion. To the extent that in-house production for consumption is still dominant in the home country, the variance with respect to intrafirm and interfirm productivities is small compared to the foreign country. To the extent that wide-spread exchange has succeeded in emerging, the home country R&D strategy may have lead to a relatively large variance.

Given these two types of conditions at time $t = \tau$, we can introduce a radical reduction in the intercountry transaction costs and follow its evolutionary consequences until time $t = T$. In this subsection this will be done without changing any other assumption about the firms and the countries, but in the next subsection additional assumptions about the second period will be made.

The first type of situation for intercountry exchange has large productivity differentials in the foreign country and normally very small differentials in the home country. In this situation intercountry trade has little influence on the relative and absolute differences with respect to the standard of living. A home firm that did not exchange before will not normally start to exchange in the new situation. Its trajectory of productivity improvement will continue in its previous slow pace. However, the home firms that did make intracountry exchanges previously may start to look for foreign partners. If some of them succeeds, other home firms may be forced back to autarky. Therefore, the overall effect on the living standard of the home country is not clear. We may, however, say something general about the bilateral exchange rate between the two firms from different countries and the terms of trade between the two countries.

Hitherto, we have not considered the distribution of the gains from exchange between the involved parties. It is obvious that the relative productivities of the trading partners in their respective areas of specialisation is of major importance. Here there is a clear asymmetry. The foreign firms have to some extent deepened their knowledge about their chosen area(s) of specialisation while the home firms are mainly influenced by a more or less systematic avoidance of the emergence of productivity differentials—except for a shorter history of specialised production. This means that foreign firms will in general have a stronger competitiveness and thus obtain a larger part of the gains of trade. In other words, the bilateral exchange rate between two firms will normally be favourable towards the foreign firm. Over time this may change, given the greater propensity of the home firm to increase productivity within its given area of specialisation. But the home firm has less means of overcoming a fall-back into autarky (because it has only one or a few goods with more-or-less competitive productivities).

There is also another type of situation for intercountry exchange where there is large productivity differences in the foreign country and but maybe even larger differences in the home country. In this situation intercountry trade has a potentially large influence on relative and absolute differences with respect to standard of living. In the home country firms have made specialisations of production and R&D that is limited by their low consumption level. But within its specialisation(s) each home firm has focussed its R&D and thus created intrafirm and interfirm productivity differences. When intercountry exchange is introduced, firms of the home country have a large chance of getting a reinforcement of their respective specialisations in the low end of the production hierarchy. In the foreign country the situation is more complex. Foreign firms that have specialised in the high end of the hierarchy will tend to have their specialisations reinforced while low-end foreign firms will often have to adjust. Given the propensity to spread R&D to a relatively large degree, many of these firms will succeed. Other foreign firms with low-end specialisations will be able to compete since they have on average a longer history of cumulative improvement of their algorithms.

The result of the introduction of intercountry exchange is likely to be quite large, measured in terms of a significant increase in living standards in both countries. Furthermore, the focussed R&D strategy of specialised home firms will on average have given them a strong competitiveness in their areas of specialisation. The foreign firms have had a less focussed strategy so their competitiveness in their own areas of specialisation tend to be weaker. Thus the home country will tend to obtain a significant part of the gains from intercountry trade, and we may see not only a major increase in the standard of living in the home country but also a significant degree of catching-up with respect to living standards. The foreign country will, however, also see an increase in its average standard of living. But for some foreign firms with low-end specialisations the consequence will be quite negative. The most successful foreign firms will reach the constraint of production and consumption set by the available product designs. So their standard of living will not change before they make product innovations.

The long term effects of the increased market is not dramatic in the present version of the model. The reason is that although there are increasing returns from the exploitation of knowledge and knowledge creation, these static and dynamic economies are limited because knowledge is private to firms and thus its exploitation is limited by the fixed size of the firm.

Intercountry exchange with new strategies

In the above experimental conditions intercountry exchange was the only event that happened at time $t = T$. Normally such a radical change in likely to be part of a package of behavioural changes. We shall shortly consider the consequences of a few further changes of the rules of the model. First, firms of both countries get access to the product innovations and product designs of the other country. Second, firms increase their R&D intensity to cope with the more competitive situation and/or the new possibilities. Third, firms change their R&D strategy to reflect the larger number of trading partners and the potentially larger range of produced goods. Fourth, the firms of the home country try to introduce mechanisms for the exchange of R&D results.

The access of the home country to foreign product designs is a major change. It means that firms can start to specialise in any product that is produced in the foreign country. However, the home firms does not have any previous accumulation of knowledge in a whole new range of goods, and it is not easy to design an R&D strategy that allows the selection of adequate specialisations in this range. At the intercountry frontier of consumption the conditions are much better. One potential strategy of home firms is be to start R&D on the algorithms for the production of a new good as soon as its product design becomes available. However, as the model is designed a firm that produces the new good both for its own consumption and as a means of producing surplus for exchange has an advantage over firms that only produces for exchange. It is only home firms at the front-end of consumption that has this advantage—and they are few.

The increased level of R&D leads to an increased competition, and the increased range of produced products leads to an increased difficulty in finding an R&D strategy that enhances the present specialisation and gives some insurance against a loss of this specialisation by building a knowledge base about a few other products. This is not at all easy. An alternative strategy is to collaborate with respect to R&D and innovative results, especially in the dominant low-end of the hierarchy of goods.

Exploring innovation systems

The above exploration of the evolutionary model has demonstrated many important problems that may be summarised under the heading: the division and specialisation of the creation of knowledge. Thereby the model moves a step beyond Adam Smith's theory of the division of labour and specialisation of firms that considers knowledge as a mere by-product of productive activities. It also moves beyond Hayek's discussion of the market system of division of a given knowledge between firms.

In the present model we have to take explicitly into account the rules of firms with respect to both R&D intensity and R&D specialisation. The evolutionary model function as a "test bed" for such rules, both the rules of thumb described in the innovation studies and a whole range of possibilities that proposes themselves from the model and have to be confronted with empirical evidence. These rules of thumb cannot always be deducted in a simple way from the decision problems of firms. Both in the model and in business practice they emerge largely due to common experience and they tend to crystallise as an interdependent set of rules, the nucleus of an innovation system, that makes it easier to survive and succeed in an open-ended evolutionary process that builds on a semi-organised version of the Schumpeterian process of creative destruction.

There is a long way from the evolutionary model to the kind of issues explored in the literature on national innovation systems and other kinds of innovation systems. The most important omission is the lacking treatment of the division of labour with respect to the individual R&D activities and to the exploitation of innovation results. This kind of issues are not easy to explore in a model of barter trade with no possibility of storing and reselling goods that are not consumed immediately. In this section we shall, nevertheless, deal with some broader issues of innovation systems in relation to the model.

Nonrival aspects of technologies

The background for the functioning of innovation systems is that innovative results—production algorithms and product designs—represent a peculiar mix of private and public goods (cf. Romer 1993b, 1993c, Nelson and Romer 1996). Technologies differ from conventional goods by not being destructed by their use. Instead a formalised technology (a product design or a process algorithm) can, in principle, be freely applied for any scale of production. The (probabilistic) costs of creating the technology can thus be spread over a larger volume of output without incurring additional costs, and this means that an increased scale of application leads to decreased average costs. The advantage from the scale of adoption of production algorithms was in the model restricted by the size of the individual firm. But the nonrival character of a technology means that it can be adopted by extra firms without influencing the production result of the present adopters.

Technologies differ from pure public goods by having some degree of excludability (or appropriability) since a firm has several methods (taciteness of technical knowledge, non-disclosure, patenting, etc.) for holding its technology to itself. This excludability explains how the expected revenues from a more or less monopolised new technology can more than outweigh its (probabilistic) costs, and thus why private firms may undertake innovative activities. However, the fact that the exclusion is often partial—as in the case of product designs—means that an externality, a knowledge spillover, arises from the creation of technology within a firm. In some cases a relatively low degree of excludability allows the free-rider strategy of the imitators to become dominant while private production of the technology becomes impossible.

To policy-makers the placing of technologies on the scale between private and public goods suggests an Arrowian dilemma (Arrow 1962) or a Schumpeterian dilemma (Nelson and Winter 1982, Ch. 14). On the one hand, a strengthening of the private good aspect of technologies by increased excludability gives incentives to private R&D but also to monopoly power and slow—if any—diffusion of technology. On the other hand, an emphasis on technologies as public goods with low excludability avoids static inefficiencies; but if growth is to be upheld in the long run, government seems to get the near-impossible task of being a major supplier of technologies. At least we have to find a private mechanism that is more convincing than the above story of foreign-country firms that in advance produced product designs which immediately spilled over to other firms.

It should be observed that individual technologies differ with respect to their intrinsic degree of excludability. First, some technologies are so idiosyncratic that they are mainly applicable within a specific firm; they can either be inherently idiosyncratic or their basic logic can intentionally kept unformalised and tacit. Second, there are technologies that are not protected in these ways, so they have to be made excludable through a more systematic effort with respect to patenting, etc. Third, there are still other technologies are related to the many minor activities that a firm perform, and no special effort is made for avoiding spillovers; on the contrary, they can allow the firm's access to "clubs" for the exchange of minor technological results. Candidates for such a treatment are the many subprocesses that was assumed to be necessary for the production of each of the goods, although this aspect was not explored in the model experiments. Finally, there are technologies for which the intrinsic excludability is so small that they are either avoided or produced through publicly supported R&D.

These different approaches to excludability are not purely theoretical. On the contrary, economic life and economic policy demonstrate continuous attempts to cope with the problems—not least through trial and error. Innovation systems reflect historically given, preliminary solutions to these problems.

Innovation systems from a public sector perspective

To understand the development of innovation systems it is not sufficient to explore the institutional evolution within the private sector. Major institutions are developed by or heavily influenced by the public sector. To avoid an assumption of the behaviour of this sector according to inherent fulfilment of the general interest, a simple background of its behaviour can be included in an extended version of the model. In this version it is assumed that each of the countries have a public sector that employs workers that are at the same time members of the labour force of individual firms (each with more than one member); each firm takes care of the consumption of the members it has transferred to the public sector. At the same time the public sector has an interest in its own expansion, e.g. because of a perceived race with the public sector of the foreign country.

The size of the public sector is determined by two taxes, a poll tax and a turnover tax. The head tax functions in a way similar to the research intensity rule of private firms: a given fraction of the labour force is transferred to the public sector. This tax obviously puts the heaviest burden on weak firms and their members. The turnover tax is related to exchanges between firms, and it functions in the same way as the model's transaction costs: it creates a gap between the costs of the supplier and the benefits of the user. Because of the way the two taxes is specified, the public sector can be dealt with by introducing a few minor complications into the specification of the model. In the main we may think of the public sector as being already implicitly present in the above accounts for the model.

The actual function of the public sector is to supplement the self-organising forces of the private sector in two respects: enhancement of the production and distribution of innovative results, and reduction of transaction costs. The former task applies even to a system of autarkic firms while the latter task is only relevant where there is at least a chance of developing an extended exchange. No attempts will be made to endogenise the public sector into the model. However, at couple of stories about the functioning of the public sector may help to motivate a further analysis of innovation systems and the public sector's role in them.

Technology centres

We are now ready to study the consequences of activity-specific technical change within firms. Even if all the firms are initially identical, they will for probabilistic reasons gradually become different. One firm will have superior productivities with respect to some activities while another firm will have superior productivities with respect to other activities. This divergence is especially strong if technological change is cumulative and if imitation is difficult—as Levin et al. (1987) have demonstrated that it often is. In this case it becomes especially obvious that as long exchange between firms is not introduced, firms will concentrate their R&D effort in a way which is exactly opposite of their productivity advantages. In other words, R&D tends to be focused on the weak spots, and replication of research results already obtained by other firms becomes the norm. But even in exchange-dominated systems, duplication of R&D results is frequent.

There are many ways of overcoming the problem of duplication. One possibility is to create "technology centres" and other forms of interfirm clearing-houses for the exchange of innovations which individually are of minor importance to the innovators but which as a whole is of major importance to a (nationally located) group of similarly specialised firms (cf. Romer 1993b). If firms exchange their marginally relevant knowledge via a technology centre, the rate of productivity increase will be much larger than if they keep the innovative results for themselves. However, "technology centres" are confronted with obvious free-rider problems. Historical experience suggests that idea of self-organising centres should not be overestimated and that the public sector normally is heavily involved. For instance, the establishment of technology centres may presuppose some degree of anticipatory policy from government because the efficiency of a technology centre may initially be rather low while a leaning process makes it better and better in performing its tasks (Galli and Teubal 1997).

It also seems to be easier to organise such centres in the weak "home" country, since here the clearing house function mixes with the technology transfer function from the foreign country. If the foreign country is advanced, we have for most goods i that

$A^{*}_{ijt} > A_{ijt}$ and $A^{\max *}_{it} > A^{\max}_{it}$. This means—as mentioned—that the home country firms normally have a bad bargaining position and bad terms of trade. Under these conditions a national innovation system than emphasises technology transfer more than intellectual property rights is an obvious possibility (cf. Freeman 1988, Lundvall 1988). However, such an innovation system is only relevant for an open weak economy. Both closed weak economies and open economies that are in some respects more or less equal partners have a different situation.

Focussed R&D through improved appropriability

Normally a major problem of the innovation system is how to stabilise the competitive conditions of firms in order to allow them to focus their research effort. In the present model the problem is that the firms that cannot find any customers for their given specialisation may fall back to a less favourable specialisation or to autarky, and thus to a low standard of living for their employees. If this risk is very large for a firm, its R&D effort will have to improve its autarkic standard of living. Under somewhat more stable conditions, the problem for the firm is to insure itself against a major backlash by performing R&D in relation not to one but a few production possibilities. This strategy is possible in the model because of an important assumption that is not made in e.g. Nelson and Winter's (1982, Ch. 5) mode. They assume that firms forget routines that are not performed continually. The present model assumes that firms are still able to perform activities although they are not practising them because of a structural specialisation.

However, it is also assumed that process and product innovation are primarily related to active tasks. This means that the productivity gap between the unchanging performance of most latent tasks and the best-practice performance will at some point of time make the specialisation irreversible. If demand is diminishing, this will threaten the existence of the specialised firm. Therefore, the main function of the different institutions that promote the appropriability of innovations (patents, etc.) is not mainly seen as influencing the share of the labour force engaged in R&D activities. It is probably of more importance that increased appropriability allows firms to focus their research and avoid the substantial costs spreading their efforts and reproducing innovations already made by other firms. In other words, the fact that pure spillovers are omitted from the present model is not accidental. Instead we might model "imitative innovations".

The productivity of research

Since we blur the distinction between imitations and innovations, we should allow some degree of spillovers in all innovations. Thus the spillovers are not direct but mediated through the probabilistic labour coefficient of research work, R_{jt}. Together with the R&D intensity (r_{jt}) this coefficient determines the arrival rate of innovations to firm j. In its turn R_{jt} is determined by two stocks of knowledge: the stock of technology-based general knowledge ("generally known algorithms"), and the stock of science-based general knowledge ("basic laws"). The stock of algorithms is not cumulative in a simple sense since each new labour coefficient represents a new algorithm that replaces the old one. Instead the stock of algorithms is assumed to be proportional to the number of sectors in the economic system (cf. Romer 1990). The stock of "basic laws" is (contrary to the proposition of Thomas Kuhn) assumed to be cumulative. It is determined by the cumulative output of the public basic research sector (and thus exogenous in the extended model). It grows at a constant rate.

Taken together the stocks of algorithms and basic laws are assumed to determine research productivity, e.g. according to a Cobb-Douglas function. This function is likely to show increasing returns to scale because innovation is to some degree a matter of making "new combinations" (Schumpeter) and the materials for making these combinations are taken from the stocks of knowledge. The function depicts the interdependence between algorithms and basic laws in research work: If a researcher has only concrete algorithms, she is in trouble applying these algorithms in new areas. If she has only basic laws, it is next to impossible to create concrete artefacts. If she has both in an adequate mix, things are much easier and her research work is much more productive. This interaction between technology and science has recently been re-emphasised by Nelson and Romer (1996).

We now have all the elements that determine the rate and direction of a firm's innovative results in the extended model. First, the overall research productivity is calculated. Second, the firm's research effort determines in a probabilistic way the number of innovations. Third, each innovation is assigned to an activity according to the firm's focusing algorithm. Fourth, the degree of spillover from other firms is calculated. Fifth, the labour coefficient that comes out of the innovation is calculated. Sixth, it is checked whether the innovation improves the firm's productivity. If this is the case, we come to the seventh and last task: to set the new productivity that is applicable to its full extent in the next period.

Conclusions

The paper presented an evolutionary model of multisectoral growth and development that is designed to allow the specification of a concept of innovation systems and to function as a test bed for the system of behavioural rules that form the core of innovation systems. The model was conceived in order to provide intermediate steps between formal growth modelling and the kind of appreciative theorising that has characterised the discussion on national innovation systems and other kinds of innovation systems.

Although an emphasis was put on the relationship with empirically oriented innovation theorists, the logic of the modelling exercise has lead in directions which might also be used in more general accounts for economic growth and development. Like in e.g. Pasinetti's growth model and much of new growth theory, the long-run consequence productivity growth in the evolutionary model is that labour becomes available for the production of new consumption goods. Like in the Pasinetti model it is noted that if such goods are not available to a sufficient degree, the macroeconomic consequence is that "technological underemployment" will emerge. A related problem, namely that productivity growth is slow for front-end goods, does not lead to "underemployment" but just to a slow-down in aggregate growth. In the former case we may talk of problems of "satiation in the narrow sense" where there is a lack of product designs for the "next" goods in the hierarchy. The latter case may be related to "satiation in the very broad sense" where the "next" goods are produced with so low productivity that they function as a brake on further growth.

Such conclusions are, however, not the primary output of the model. Instead the model has served to draw the attention to some of the problems related to the way economic systems organises their production of knowledge. Even in the model's simple economies with multisectoral bilateral exchange, it became obvious that firms have problems in determining the size and the specialisation of their R&D efforts. There is no obvious way of finding the best solution to this problem. Instead groups of interdependent firms have to rely on a system of heuristic rules that often are initially found within countries. The study of such heuristic rule systems seems to be an important starting point for the analysis of the empirical phenomena related to what has been called national innovation systems.

Although the model has in several ways been inspired by endogenous growth theory, it has a very different approach. The most obvious mark of distinction is the introduction of the possibility of autarky through the use of consumer-producer firms. The introduction of such firms also allowed the exclusion of factor markets and thus they allowed simple mix of competition, increasing returns and endogenous R&D. But the purpose was not to produce yet another endogenous growth model. Actually, one of the major points of the modelling exercise has been to demonstrate that there is no such thing as a full long-term endogeneity of growth and development. During the long-term evolutionary process of growth and development the specialisation and exploitation of knowledge creation will once in a while run into problems that cannot be solved by means of the existing behavioural rules. Thus there is a need of innovating the given innovation systems. Such meta-innovations cannot be fully endogenised. But the present model might suggest some of the problems that meta-innovations have to overcome.

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