A model of intersectoral flow of technology using technology and innovation flow matrices

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1 INTRODUCTION

Complementarity among heterogeneous technologies constitutes a major characteristic of technological change (Rosenberg, 1982). The importance of complementarity implies that sufficient attention should be paid to intersectoral effects of technological change. For example, it is acknowledged that a few key industries, called general purpose technology (GPT) sectors, play an important role in generating economic development and growth (see for example, Bresnahan and Trajtenberg, 1995; Helpman, 1998; Harada, 2010). However, the endogenous growth literature has not yet fully incorporated the intersectoral effects of technological change into its formal models. Although a product-variety version of the endogenous growth literature (Grossman and Helpman, 1991) is a multi-sector model, it assumes a fixed and identical input structure for all sectors, so that asymmetric intersectoral effects of technological change are excluded a priori.

The literature on input-output analysis takes the intersectoral relations in commodity transactions into account. In addition, a large number of empirical input-output based studies have shifted the attention from commodity transactions to R&D spillovers. They have constructed technology flow matrices showing intersectoral technology flows (or intersectoral spillovers) (Scherer, 1984; DeBresson, 1996; Keller, 1997; Kortum and Putnam, 1997; Verspagen, 1997; Meyer, 2002; Nomaler and Verspagen, 2008; Montresor and Vittucch Marzetti, 2009; Düring and Schnabel, 2010; Gehringer, 2012).[1] These matrices trace the intersectoral technology flows on the basis

[1] Several other terms are used besides “technology flow matrix”, such as “knowledge flow matrix”, “invention input-output matrix”, “innovation flow matrix”, and “R&D flow matrix”, most of which

of patent citations, industrial publications, and university patenting (Meyer, 2002). Alternatively, sector-level R&D data and coefficients of input-output tables are used to approximate technology flows (see, for example, Keller, 1997; Montresor and Vittucci Marzetti, 2009). These empirical studies have succeeded in revealing the importance of intersectoral technology flows in generating economic growth. However, their micro-foundations are still ambiguous, because they are not built upon a general equilibrium framework.

Although some attempts have been made to fill the gap between input-output analysis and the endogenous growth literature (Los, 2000; Harada, 2015), an input-output model that completely accounts for the intersectoral aspect of technological relations with a rigid micro-foundation remains undeveloped. The empirical work by ten Raa and Wolf (2000) is one of a few exceptions, in that it derived the intersectoral spillover relations from a standard neoclassical general equilibrium framework. However, this paper differs from their work in the sense that we explicitly model the production of technology in sectors and regard R&D spillovers as the result of technology transactions across sectors, rather than as external economies. One of the advantages of this approach lies in the new theoretical perspective on intersectoral technology flows (see for example, Harada, 2015) and its computational ease and simplicity.

This paper aims to build a bridge between endogenous growth and input-output literature by using an intersectoral general equilibrium model that directly focuses on

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refer to the same concept. For surveys, see Evenson and Johnson (1997), Mohnen (1997) and Los and Verspagen (2007). In this paper, we conceptually distinguish between technology and innovation flow matrices.

the propagation patterns of technology and innovation across sectors. This model assumes that an economy stays on a balanced growth path from the beginning, which is the result of an endogenous growth mechanism. In addition, this model assumes that the technology and innovation flow matrices relate technology and innovation to each intermediate sector. Then, we introduce the production structure of technology in which technology is a system consisting of many (technology) components (for example, automobile technology consists of material, mechanical, electronics, chemical, and information and communication technologies as technology components). So the latter technology components are used as inputs to produce the technology. Meanwhile, technology and innovation flow matrices determine the intersectoral technology flows. In this model, technology is not given but is produced through technology transactions. Based on this technology production structure, we can empirically evaluate how productivity shocks (as deviations from a balanced growth path) are propagated across sectors, which has been overlooked in the endogenous growth literature. Moreover, we are able to reveal the underlying micro-foundation for technology and innovation flow matrices. Hence, the model in this paper blends both endogenous growth and input-output models in a consistent manner.

However, our model is not a mere blend of these two approaches. First, it sheds new light on the mechanism of intersectoral technology flows by explicitly modeling the production of technology using diverse technology components as inputs. In other words, while related models leave aside the mechanism of technology production, the model in this paper focuses on this production structure. Second, we conceptually distinguish between technology and innovation flow matrices. In this study, “technology flow matrix” refers to the pattern of technology transaction without innovation. In other words, this matrix describes the transaction patterns of technology components for each technology (for example, it describes how automobile technology is produced using mechanical, electronics, chemical and IT technology components as inputs). At this stage, no innovation takes place in each technology component. Once innovation occurs in some technology component, "innovation flow matrix" describes how a given innovation is propagated across sectors. This matrix is required because innovation might change the current transaction pattern of technology components. For example, in the production of automobile technology, innovation in information technology component might reduce the demand for mechanical technology component. These matrices should be conceptually distinguished from a standard input-output matrix because the latter primarily describes commodity transactions, rather than technology transactions themselves, though both are closely related.[2] Third, our technology and innovation flow matrices do not necessarily refer to technology spillovers alone, they also describe the pattern of intersectoral technology flows as a result of economic activity across sectors where the value of each technology component is evaluated at factor prices and no free lunch is assumed. In short, the main contribution of this paper is to reveal the economics of technology production and intersectoral technology flows in a general equilibrium framework.

As a quantitative exercise based on this model, its theoretical predictions are examined using recent Japanese R&D investment data collated at the two-digit standard industrial classification (SIC) code level. These data indicate that technology shocks are generally localized within sectors, whereas asymmetric intersectoral effects are

[2] Hence, the approach to construct technology flow matrix based on the input-output matrix cannot be justified. This was also pointed out by Evenson and Johnson (1997).

observed in GPT sectors such as IT, precision instruments and motor vehicles.

The rest of the paper is organized as follows. In Section 2, a basic model of intersectoral technology flows is described and its equilibrium properties are derived. Section 3 examines the intersectoral effects of technology shocks along with a simple quantitative analysis using recent Japanese R&D data. Section 4 presents the conclusions.

2 THE MODEL

In this section, a model of intersectoral technology flows is developed. This model differs from the related literature as the production of technologies is explicitly specified.

2.1 Outline of the model

Consider a discrete time closed economy with one final product (commodity) and n technology components, the latter being produced by intermediate (technology component) sectors. An intermediate sector supplies one unit of technology to itself and to other intermediate sectors, as well as to the commodity producer. Both the intermediate and commodity sectors use labor and technology components as inputs. Thus, in this economy, physical intermediate inputs are assumed away to simplify the analysis and focus attention on technology and innovation aspects of the economy. Because technology exists in a non-physical form that is similar to blueprints (i.e. knowledge), technology components are regarded as representing knowledge.

Knowledge is duplicated without additional costs. Therefore, the quantity of technology components has no relevance and the quality level alone matters in this economy.

We assume that the economy is already on a balanced growth path that is caused by some endogenous R&D investment, as described in the endogenous growth literature. Although it is not difficult to explicitly incorporate this endogenous growth aspect into the model, we prefer to maintain the assumption of the balanced growth path from the beginning. The reasons for this are twofold: first, this assumption makes the model less complicated and easier to understand, and second, the growth endogeneity has no direct implication to our empirical exercise. Because the balanced growth path has already been well accounted for by the related literature, we will focus on the intersectoral technology flows and innovation along the balanced growth path. In other words, the model in this paper is concerned with the propagation mechanism of a *given* innovation rather than the innovation mechanism per se.

In each period, a technology component has to be produced by the corresponding intermediate sector. Each technology component is produced by using labor and its own and other technology components as inputs. Because this model is directly concerned with the production of technology, a change in the quality level is referred to as "technological change" or "innovation". This is caused by demand or technology shocks, which are deviations from the balanced growth path. As long as the prices and production functions of the intermediate sectors remain the same, innovation does not take place as the quality of each component is fixed. Given the result of past innovation, each sector produces technology of a specified quality.

The commodity sector uses the produced technology components and labor for the production of the commodity. Thus, two stages of production prevail in this economy. In the first stage, a commodity producer announces the demand for each technology component. Following this announcement, the technology components are produced by intermediate sectors. In the second stage, the commodity producer produces the commodity and supplies it to the household. Perfect foresight is assumed such that the realized quality level of each technology component in the first stage is correctly predicted by the intermediate sectors and the commodity producer.

It is also assumed that the technology components and the commodity are produced according to an o-ring type production function. Kremer (1993) proposes an o-ring production function that incorporates the fact that mistakes in any series of tasks can dramatically reduce the products value. In this paper we suppose that the production function represents a technological system. This consists of a series of interrelated technology components or component technologies. Thus, in our model the series of tasks are regarded as a series of technology components which are provided by their own sector as well as other sectors in an economy.

In this model, because the economy is assumed to stay on a balanced growth path, equilibrium consists of static assignment of quality levels, prices, labor and consumption across intermediate and commodity sectors. More specifically, equilibrium is defined as:

1. determination of factor prices for technology components paid by intermediate sectors;
2. determination of quality levels for technology components;
3. determination of factor prices for technology components paid by a commodity producer;
4. labor assignment for each intermediate sector and commodity producer;

5. labor market clearing condition;
6. determination of consumption of a commodity by a representative household.

These prices, payments, labor employment and consumption are to be determined such that the intermediate and commodity sectors maximize their profits and the representative household maximizes intertemporal utility while satisfying the labor market clearing condition. Note that because the quantity of technology components and commodity has no relevance in this model, the market clearing condition matters only for labor.

2.2 Production of technology

There is an indefinite supply of potential firms in the intermediate sectors and all have the production function

$$q_j = A_j l_j^{\alpha} \prod_{i=1}^{n} q_{i,j}, \tag{1}$$

where the subscript j refers to the jth sector, A_j and l_j denote the productivity level and labor employed in this sector. $q_{i,j}$ is the quality (technology) level of the technology component i used in the production of the jth technology component and $0 < \alpha < 1$.

As we described above, each technology component is assumed to represent specific knowledge corresponding to its technology field. Therefore, the production function (1) specifies the production of knowledge in which technical knowledge is produced using the variety of knowledge as inputs. When the technology component as knowledge is produced, it is supplied to its own sector, other intermediate sectors, and the commodity sector.[3]

To simplify the notation and algebra, capital is not included in this production function. This exclusion is justifiable because its inclusion does not affect the qualitative results of this paper. In addition, we are primarily interested in empirically examining intersectoral flow of productivity shocks, which are independent of capital and labor inputs (as the Solow residuals indicate).

To highlight and analyze this intersectoral innovation flows more explicitly, we take the knowledge perspective in which each technology component is regarded as representing specific knowledge. Indeed, many final and intermediate products consist of a number of parts and materials. Consequently, the increasing division of knowledge and labor prevails to such an extent that most of the products cannot be produced without outsourcing. From the knowledge perspective, this implies that each product is produced using the diverse knowledge. Therefore, the production function (1) reflects this division of knowledge in the production of knowledge. The critical difference here is that the intersectoral model in this paper allows for the diversity of technological interdependence among technology components, while the multi-sector endogenous growth model that is used in the literature only assumes a fixed symmetric interdependence. Knowledge is assumed to be protected by a patent so that it cannot be used without payment to the corresponding supplier (i.e. owner). The supplier of

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3 It may seem logically impossible that a sector produces its own output using part of its output as an input. One interpretation is that the sector needs to use some of its output to test quality levels. It should be noted that the results in this model do not depend on $q_{j,j} > 0$.

technology component i in the j th sector with the quality level of $q_{i,j}$ then receives a payment of $p\left(q_{i,j}\right)$ from the sector. The risk neutral j th sector maximizes the profits as

$$\max_{q,l} \overline{P}_j A_j l_j^{\alpha} \prod_{i=1}^{n} q_{i,j} - \sum_i p\left(q_{i,j}\right) - w l_j, \tag{2}$$

where $\overline{P}_j$ denotes the quality adjusted price of the j th technology component. As we will see, $\overline{P}_j$ is derived from the sum of payments *received* from intermediate sectors and the commodity sector [see (19)]. Meanwhile, w is determined to equate a labor market clearing condition [see (16)]. Hence, it would be innocuous to assume that each intermediate sector takes them as given. However, the payment *given* to the i th supplier, $p\left(q_{i,j}\right)$ is directly determined by the choice of the quality level, $q_{i,j}$. Therefore, each sector maximizes its profits with respect to $q_{h,j}$ and l_j in (2), taking into account that $p\left(q_{i,j}\right)$ is affected by its own choice.

The first order conditions are:

$$\overline{P}_j A_j l_j^{\alpha} \prod_{i \neq h}^{n} q_{i,j} = p'\left(q_{h,j}\right), \tag{3}$$

$$l_j = \left(\alpha A_j P_j w^{-1} \prod_{i=1}^{n} q_{i,j}\right)^{\frac{1}{1-\alpha}}. \tag{4}$$

From (1) and (4), we have

$$wl_j = \alpha P_j, \tag{5}$$

where $P_j = \overline{P}_j q_j$. This suggests that the labor budget share is α.

From (3) and (4), we derive

$$p'\left(q_{h,j}\right) = \left(\alpha^{\alpha} A_j P_j w^{-\alpha} \prod_{i \neq h}^{n} q_{i,j}\right)^{\frac{1}{1-\alpha}} q_{h,j}^{\frac{\alpha}{1-\alpha}}. \tag{6}$$

2.3 Factor price

Intermediate suppliers provide one technology component unit inelastically to each intermediate sector and the commodity producer. Suppose that the quality levels are represented by a quality ladder (see for example, Aghion and Howitt, 1992)

$$q_{i,j} = q^{\mu_{i,j}}, \tag{7}$$

where $q > 1$ and $\mu_{i,j}$ takes positive values, representing the current quality level. Using (7) and (6), it is rewritten as

$$p'\left(q_{h,j}\right) = \left(\alpha^{\alpha} A_j \overline{P}_j w^{-\alpha}\right)^{\frac{1}{1-\alpha}} q^{-\mu_{h,j} + \frac{\sum_{i=1}^{n} \mu_{i,j}}{1-\alpha}} = \left(\alpha^{\alpha} A_j \overline{P}_j w^{-\alpha}\right)^{\frac{1}{1-\alpha}} q_{h,j}^{-1+\frac{\sum_{i=1}^{n} \mu_{i,j}}{(1-\alpha)\mu_{h,j}}}. \tag{8}$$

We assume free entry into each intermediate sector so that each supplier earns zero profits. Following Kremer (1993), we have integrated this marginal condition with respect to $q_{h,j}$ and obtain the factor price schedule of technology component h as

$$p\left(q_{h,j}\right)=\left(1-\alpha\right)\theta_{h,j}\bar{P}_j q_j=\left(1-\alpha\right)\theta_{h,j}P_j, \tag{9}$$

$$\theta_{h,j}=\frac{\mu_{h,j}}{\sum_{i=1}^{n}\mu_{i,j}}, \tag{10}$$

where $P_j\equiv\bar{P}_j q_j$ and $\sum_h \theta_{h,j}=1$. Therefore, we can confirm that the sector indeed earns zero profits because αP_j is paid to labor and higher quality components receive more payments.

2.4 Technology and innovation flow matrices

As we have described above, each technology component represents knowledge and it can be duplicated without additional costs. Hence, the allocation of a technology component across sectors does not require the equality of supply and demand. Instead, we assume that it is allocated to each sector as

$$\mu_{i,j}=\vartheta_{i,j}\mu_i, \tag{11}$$

where $\vartheta_{i,j}>0$ is the degree of technology transfer from the i th technology component to the j th intermediate sector and $\mu_i\equiv\sum_{h=1}^{n}\mu_{h,i}$ measures the total quality level of the i th component. The magnitude of $\vartheta_{i,j}\geq 0$ is determined based on technological interdependence between the two components and the absorptive capacity of the jth sector. Therefore, it is assumed to be constant in this model. Note that this magnitude must be non-negative. If it is negative, then the jth sector has no incentive to use the ith technology component as an input. In this case, $\vartheta_{i,j}$ becomes zero. Because duplication costs are zero, we do not require $\sum_j \vartheta_{i,j} = 1$.

Without productivity shocks, the matrix $\Psi = \left[\vartheta_{i,j}\right]$ can be referred to as a *technology* flow matrix. In other words, this matrix shows the technological interdependence among technology components in a steady state. However, when productivity shocks take place, the innovation linkages cannot be measured by Ψ. To see this, from (7) and (11) the productivity growth can be derived as

$$\hat{q}_{i,j} = \eta_{i,j}\vartheta_{i,j}\hat{q}_i, \tag{12}$$

where ^ denotes the growth rate (e.g., $\hat{q} \equiv \dot{q}/q$, $\dot{q} \equiv \partial q/\partial t$), and $\eta_{i,j}$ represents the impact of innovation of the ith component on the current productivity of the jth sector. If $\eta > 0$, innovation is complementary to the current productivity. Conversely, if $\eta < 0$ then it is substitutable and has a negative effect on the current productivity. Finally, $\eta = 0$ implies that there is no innovation effect.

From (1) and (12), we obtain

$$\begin{bmatrix} \hat{q}_1 \\ \vdots \\ \hat{q}_n \end{bmatrix} = \begin{bmatrix} \hat{A}_1 \\ \vdots \\ \hat{A}_n \end{bmatrix} + \alpha \begin{bmatrix} \hat{l}_1 \\ \vdots \\ \hat{l}_n \end{bmatrix} + \begin{bmatrix} \gamma_{1,1} & \cdots & \gamma_{1,n} \\ \vdots & \ddots & \vdots \\ \gamma_{n,1} & \cdots & \gamma_{n,n} \end{bmatrix}' \begin{bmatrix} \hat{q}_1 \\ \vdots \\ \hat{q}_n \end{bmatrix},$$

where $\gamma_{i,j} \equiv \eta_{i,j}\vartheta_{i,j}$. In matrix notation, this is rewritten as

$$\hat{Q} = \hat{A} + \alpha\hat{L} + \Gamma'\hat{Q}. \tag{13}$$

Γ' indicates how productivity shock in each sector is related to the others. Solving this for $\hat{Q}$ yields

$$\hat{Q} = \left(I - \Gamma'\right)^{-1}\left(\hat{A} + \alpha\hat{L}\right). \tag{14}$$

In this equation, $\left(I - \Gamma'\right)^{-1}$ is a familiar form of a standard Leontief model and corresponds to an *innovation* flow matrix. This matrix allocates productivity shocks to each intermediate sector and determines quality levels in a new steady state. Then, the allocation of a technology component across sectors follows a technology flow matrix, Θ. If technological interdependence and absorptive capacity do not change after productivity shocks, Θ remains the same as before.

One implication of this equation is that growth rates critically depend on this innovation flow matrix. For example, even if several countries face the same technology shocks, their growth rates will differ if their innovation flow matrices are not the same. Moreover, the innovation flow matrix immediately reveals the following result:

Proposition 1: Sectoral technology shocks induce sectoral innovation *asymmetrically.*

The technology shocks induce asymmetric innovation unless $\left(1-\Gamma'\right)^{-1}=\left(1-\Gamma'\right)^{-1'}$. For example, even if technology shocks take place in the j th sector, this sector may not be able to increase quality levels substantially. Instead, other sectors could gain from the shocks and significantly increase quality levels. To correctly predict the impact of technology shocks, we need to empirically evaluate $\left(I-\Gamma'\right)^{-1}$. Impacts cannot be theoretically predicted unless Γ is fully endogenized in the model.

2.5 Household and commodity

The representative household maximizes its intertemporal utility function with a discount rate ρ. Suppose a representative household has a standard constant relative risk aversion type utility function. Because the economy is assumed to be in a steady state, and assuming that the interest rate is equal to ρ, then expenditure is constant over time. In each period it is spent on the consumption of a commodity alone with no saving. The commodity is produced according to the production function of

$$Y=\tilde{L}^{\beta}\prod_{j}\tilde{q}_{j}, \tag{15}$$

where $\tilde{L}$ denotes the labor used for the production of the commodity and $\tilde{q}_j$ is the quality level supplied by the j th sector. From the analysis above, βE goes to labor and $\left(1-\beta\right)E$ is spent on technology components where $E=w\left(\tilde{L}+L\right)\equiv w\overline{L}$ and

$L = \sum_{j=1}^{n} l_j$. $\bar{L}$ denotes the total amount of labor in this economy.

Because labor can move freely between the production of a commodity and technology components, the equilibrium condition requires

$$\frac{L}{\tilde{L}} = \frac{1-\beta}{\beta}.$$

The labor market clearing condition becomes

$$L = \left(1-\beta\right)\bar{L}. \tag{16}$$

Using the result from (9), the payment to the j th technology component by the commodity sector is

$$\tilde{P}_j = \left(1-\beta\right)\tilde{\theta}_j w\bar{L} = \tilde{\theta}_j wL, \tag{17}$$

where $\tilde{\theta}_j \equiv v_j \mu_j \Big/ \sum_h v_h \mu_h$ is the j th sector's share of the total quality level with $\sum_j \tilde{\theta}_j = 1$, and v_j denotes the j th sector's quality level used in the production of the commodity.

From (17), we have

$$\sum_j \tilde{P}_j = wL. \tag{18}$$

That is, the total amount of the final demand is equal to the total labor costs in the production of technology components.

2.6 Equilibrium

To derive P_j, those of other sectors must also be determined. From (9), we have

$$P_j = (1-\alpha)\sum_i \theta_{j,i} P_i + \tilde{P}_j. \tag{19}$$

Therefore, we can construct a system of equations as

$$\begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix} = (1-\alpha)\begin{bmatrix} \theta_{1,1} & \cdots & \theta_{1,n} \\ \vdots & \ddots & \vdots \\ \theta_{n,1} & \cdots & \theta_{n,n} \end{bmatrix}\begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix} + \begin{bmatrix} \tilde{P}_1 \\ \vdots \\ \tilde{P}_n \end{bmatrix}, \tag{20}$$

where, as we have already seen in (10), $\theta_{i,j}$ denotes the budget share of the ith technology component in the production of the jth technology component with $\sum_i \theta_{i,j} = 1$. In matrix notation, we rewrite this as

$$P = (1-\alpha)\Theta P + \tilde{P}. \tag{21}$$

Solving this for P yields

$$P = \left(I - (1-\alpha)\Theta\right)^{-1} \tilde{P}. \quad (22)$$

It is noted that if the labor share of the j th sector is equal to the final demand (i.e. $\tilde{P}_j = wl_j$ for all j) then it causes a singularity problem in (22) because $\tilde{P}_j = \alpha P_j$ holds in this case. To exactly identify P, the total value of technology components should not be proportional to its total quality level in at least one sector. That is, $\tilde{P}$ and $l = (l_1, \cdots, l_n)'$ are linearly independent. We assume that this linear independence holds here. This assumption is also familiar in standard input-output analysis.[4]

Equation (22) suggests the total value of a technology component, P_j, is not directly proportional to the quality level ϑ_j and its final demand $\tilde{P}_j$. This result is shown as $\left(I - (1-\alpha)\Theta\right)^{-1}$ in (22). To correctly predict the effect of final demand we should evaluate the values of $\left(I - (1-\alpha)\Theta\right)^{-1}$. This prediction cannot be based on purely theoretical arguments unless Γ is endogenously determined by the model.

Because the effect of productivity change is completely determined by (14), we can derive the following result:

Proposition 2: A change in factor prices does not induce innovation.

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[4] Suppose X, F and A represent total output, final demand and input-output matrix. We can derive $X = (1-A)^{-1} F$. If $F = \eta X$ for some $\eta > 0$, this equation is unsolvable unless $(I-A)^{-1}\eta = I$ always holds.

According to (22), price changes only affect the distribution of revenues with quality levels remaining constant because each intermediate supplier is assumed to supply quality inelastically and constant returns to scale prevail in the production function.

In equilibrium, q_i and $q_{i,j}$ are determined by (11) and (14). Prices are specified by (17) and (22) with $2n+1$ unknown parameters and $2n$ equations. Imposing $w=1$ we can determine the values of P and $\tilde{P}$. The amount of labor is obtained by (5). The market clearing condition is satisfied by (16). This completes the description of the model in this paper.

3 QUANTITATIVE ANALYSIS

We have seen that demand shocks cannot induce innovation, while technology shocks induce asymmetric innovation linkages among intermediate sectors. In this section, we empirically examine the implications of these results by measuring the intersectoral effects of technology shock as an illustration of quantitative analysis based on the model that is developed in this paper. We examine the intersectoral effects of technology shocks using recent Japanese R&D data. A firm belonging to a particular sector can make R&D investments in several technology fields. A firm may conduct research in other technology fields, as well as its own field, because of technological complementarity. The "Survey of Research and Development" is published annually by the Ministry of Internal Affairs and Communications in Japan and it reports R&D statistics for expenditure across different sectors at the two-digit SIC level. We use these data in our study to construct the corresponding innovation flow matrix.

For this purpose, following the common assumption of endogenous growth literature, we make a simplifying assumption that R&D is proportional to the magnitude of productivity gain captured by its investor. The data on sectoral R&D expenditure can then be used to calculate $(1-\Gamma')^{-1}$ (this is described in detail in the Appendix).

Based on the calculated $(1-\Gamma')^{-1}$, Table 1 shows total, direct and indirect effects of innovation. The total effect is measured by a column sum of this matrix. The direct effect refers to the effect of technology shock on its own sector, whereas the indirect effect measures the effect on other sectors. The former is indicated in diagonal elements and the latter calculated as a column sum of off-diagonal elements. Table 1 shows these effects:

(Table 1)

Table 1 indicates that the direct effects are close to 100% for all sectors. This dominates the indirect effects in all sectors. The results are quite intuitive because a technology shock in one sector directly improves productivity in that sector. There are strong multiplier effects in pharmaceutical, IT equipment and motor vehicle sectors.

Regarding indirect effects, the table shows that IT equipment has the highest indirect effects of 9.7% compared with other sectors. This implies that a technology shock in IT enhances the sum of the productivities of other sectors by 9.7%, thus identifying a significant effect of the IT sector.

The second highest layer of indirect effects is on precision instruments (4.6%), followed by motor vehicles (4.2%) and household electrical appliances (HEAs) (3.6%). Surprisingly, precision instruments exert the highest effect next to IT. This result is somewhat expected because motor vehicles and HEAs are key Japanese industries.

Therefore, there are two main results of our calculation of the matrix. First, the effects of technology shocks are generally localized within each sector. This implies that technology shocks are asymmetric because they are sector specific. Second, a few sectors exert significant intersectoral effects. Table 2 shows the details of indirect effects of IT, precision instruments, motor vehicles and HEAs on other sectors to see whether the latter effects are asymmetric or not. Table 2 suggests that their effects are asymmetric and localized in some sectors. For example, IT has strong indirect effects on machinery, electronics and precision instruments but other sectors gain little indirect benefits from the IT sector. These results confirm the asymmetric effects of technology shocks as well as their localized nature.

(Table 2)

Therefore, our crude empirical analysis indicates that most sectors are localized within their own sectors, whereas some GPT sectors exert significant intersectoral effects. However, the latter effects are also localized in some sectors. These results appear to support proposition 1 (i.e. the asymmetric nature of innovation effects).

4 CONCLUSION

In this paper, we have developed an equilibrium model of intersectoral technology flows using an o-ring production function. Its equilibrium is described by three matrices, Θ, $\left(I-\Gamma'\right)^{-1}$ in (14) and $\left(I-\left(1-\alpha\right)\Theta\right)^{-1}$ in (22). Θ is the technology flow matrix, specifying the quality levels of all sectors in the economy, $\left(I-\Gamma'\right)^{-1}$ is the innovation flow matrix determining the growth dynamics of the economy, and $\left(I-(1-\alpha)\Theta\right)^{-1}$ specifies their factor prices.

One of the advantages of this model is that it allows for complete general equilibrium specification. Hence, it avoids some of the criticism made about standard input-output analysis and its extreme assumptions on linear production functions and partial equilibrium properties.[5] Moreover, the model in this paper differs from related literature in that technology production and transaction is explicitly specified. Therefore, it is able to shed new light on intersectoral productivity spillover from a different perspective. In other words, this is the result of economic activities as well as technological properties. Another advantage of this model is that its analytical simplicity and tractability with minimum computational burden makes it easier to implement empirical studies.

Conversely, a disadvantage of this model lies in the empirical precision of its R&D table, such as Table 1. The justification for this calculation is attributed to the common assumption of endogenous growth literature, which states that R&D is proportional to productivity gain. However, this assumption must also be tested by resorting to other measures of productivity, such as TFP. Therefore, the validity of empirical analysis critically depends on the proximity between R&D and productivity gain.

Despite this limitation, we still believe that the empirical study based on the existing R&D table provides useful insights regarding innovation policy. That is,

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[5] Of course some input-output models also address these criticisms (see for example, Ten Raa and Mohnen, 1994; Rose and Casler, 1996; Liew, 2000).

effective innovation policies could be formulated and implemented based upon the empirical evaluation of the inverse matrix, $(1-\Gamma')^{-1}$. These policies could more precisely take into account the intersectoral effects that are illustrated by our investigation.

Economic growth and technological change have attracted much attention amongst mainstream economists for decades. Although a number of sophisticated models have been proposed, little attention has been paid to intersectoral relations and the propagation mechanism of technological change. However, as Rosenberg (1982) points out, one of the characteristics of modern technological change is complementarity among heterogeneous technologies. Therefore, to further explore inside a black box, input-output analysis regarding intersectoral technology flows should be taken into serious account both theoretically and empirically. In other words, economic growth should be more precisely analyzed in terms of the intersectoral effects summarized by technology and innovation flow matrices where multiplier, weak or independent intersectoral effects could emerge.

This paper is a first attempt at providing a theoretical justification for technology and innovation flow matrices with simple quantitative analysis. More theoretical and empirical studies are needed. These studies could lead to more effective innovation policy.

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Appendix

Data source

For the construction of Γ', we collected data from the "Survey of Research and Development" published annually by the Ministry of Internal Affairs and Communications in Japan (http://www.stat.go.jp/english/data/kagaku/index.htm). This survey collects data on intramural R&D expenditure by Japanese industries. Data for 2011 were analyzed.

Matching between sectors and technology fields

The data shows the distribution of R&D expenditure, by sector, over 30 technology fields. It is primarily classified at a two-digit SIC level. To achieve a one-to-one alignment between sectors making R&D investment and technology fields, the technology field titled "other manufactured products" was dropped from our matrix as it was difficult to identify the corresponding sectors. All other technology fields were identified in the sectors appearing in the dataset. Most sectors are classified at the two-digit SIC level although, "chemical fiber", "household electrical appliances", "aircraft", "rolling stock" and "precision instruments" are matched with the corresponding sectors at the three-digit level.

Construction of the innovation flow matrix

Following the common assumption in the endogenous growth literature, we make a simplifying assumption that states that R&D investment is proportional to the magnitude of productivity growth. Under this condition, suppose the total amount of R&D investment in the i th technology field by all sectors is R_i. If the j th sector makes R&D investment in this field by $R_{i,j}$, then this sector gains the productivity growth of $\left(R_{i,j}/R_j\right)\hat{q}_j$. However, as the quality levels and the difficulty of R&D are not the same across different technology fields, we have attached some weight to this ratio. For this weight, we used the ratio R_j/R where R denotes the total R&D investment in the economy. The magnitude of productivity growth can then be gained by the j th sector in the i th technology field is $\gamma_{i,j} = R_{i,j}/R$. Based on this specification, Γ' was calculated.

TABLE 1. Total, Direct, and Indirect Effects

Sectors/Technology fields	Total	Direct	Indirect
1. Agricultural, forest and fishing products	1.00073	1.0002	0.000529
2. Mining	1.00079	1.00075	4.21E-05
3. Building construction and civil engineering	1.0101	1.00865	0.001449
4. Food products	1.01532	1.01395	0.00138
5. Textile products	1.00177	1.00123	0.00054
6. Pulp and paper products	1.00265	1.00228	0.000374
7. Printing and publishing	1.00161	1.00113	0.000472
8. Chemicals (fertilizer, inorganic, organic)	1.03927	1.02612	0.013145
9. Chemical fiber	1.00286	1.00129	0.001568
10. Oils and paints	1.00741	1.00669	0.00072
11. Drugs and medicines	1.13924	1.12849	0.010753
12. Other chemical products	1.03739	1.0122	0.025185
13. Petroleum and coal	1.00284	1.00244	0.000399
14. Rubber products	1.01164	1.01093	0.00071
15. Ceramic and stone, and clay products	1.00915	1.00731	0.00184
16. Iron and steal	1.01081	1.00982	0.00099
17. Non-ferrous metals	1.00854	1.00627	0.002278
18. Fabricated metal products	1.00561	1.00323	0.002384
19. General machinery	1.078	1.05663	0.021366
20. Household electrical appliances	1.03958	1.00334	0.036244
21. Other electric equipment	1.04963	1.02265	0.02698
22. Information and communication equipment	1.27498	1.17753	0.097453
23. Motor vehicles	1.26757	1.22592	0.041651
24. Aircraft	1.00458	1.00066	0.003919
25. Rolling stock	1.00093	1.00012	0.000807
26. Other transport equipment	1.00526	1.00163	0.003632
27. Precision instruments	1.06698	1.02065	0.046331
28. Electricity and gas	1.00674	1.00582	0.00092
29. Software and information processing	1.0365	1.01975	0.016752

TABLE 2. Indirect Effects of Key Sectors

Sectors/Technology fields	IT	Precision	Motor	HEA
1. Agricultural	5.54D-10	7.03D-10	1.41D-10	3.62D-11
2. Mining	4.44D-07	3.33D-08	3.34D-08	1.32D-08
3. Building construction	0.000467	6.92E-05	6.23D-06	1.31E-05
4. Food products	5.39D-06	6.83D-06	1.37D-06	3.52D-07
5. Textile products	0.000677	6.75E-05	0.000681	2.84E-05
6. Pulp and paper products	1.18D-07	2.34D-07	5.01D-08	6.10D-09
7. Printing and publishing	0.001268	6.56E-05	2.36D-06	3.35E-05
8. Chemicals	0.003285	6.94E-05	0.000148	9.62E-05
9. Chemical fiber	0.000657	6.58E-05	0.000509	1.75E-05
10. Oils and paints	0.000402	0.000214	0.000364	3.26E-05
11. Drugs and medicines	3.95E-05	0.000333	0.000125	2.91E-05
12. Other chemical products	0.000136	0.000447	8.85E-05	7.59D-06
13. Petroleum and coal	0.000108	7.77D-07	3.98D-07	2.87D-06
14. Rubber products	4.51E-05	4.5E-05	0.000161	1.21E-05
15. Ceramics	0.001711	7.23D-06	0.00055	4.56E-05
16. Iron and steal	0.000815	6.67E-05	0.000284	2.24E-05
17. Non-ferrous metals	0.005323	5.56E-05	0.00116	0.000143
18. Fabricated metal products	0.000203	6.76E-05	0.001135	9.26E-05
19. General machinery	0.039623	0.041135	0.00465	0.001778
20. Household electrical appliances	0.000143	1.86E-05	7.76E-05	-
21. Other electric equipment	0.016834	0.000127	0.029656	0.00207
22. IT equipment	-	0.002856	0.001866	0.031098
23. Motor vehicles	0.000167	0.00039	-	1.42E-05
24. Aircraft	6.16E-05	5.19E-05	8.81E-05	2.19D-06
25. Rolling stock	6.40D-07	8.99D-06	2.85D-06	4.36D-08
26. Other transport equipment	5.8E-05	8.33E-05	3.11E-05	2.37D-06
27. Precision instruments	0.02387	-	5.59E-05	0.00066
28. Electricity and gas	1.56E-05	1.6E-05	2.20D-06	7.19D-07
29. Software and information	0.001537	6.3E-05	5.30D-06	4.1E-05