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Innovation and Upgrading in Global Production Networks*

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Abstract

This paper deals with the role of innovation in upgrading within global production networks (GPNs). Because of the distribution of production segments across firms and countries, there is also a distribution of production knowledge. The paper looks at some ways of upgrading by developing economy firms–the roles of distributed knowledge, reverse innovation and new types of innovation, based on frugal engineering in emerging economies. Process changes could also be innovation, though, unlike product innovations, they are easily copied and spread. The paper points out the limits of current reverse innovation and also asks whether the separation of manufacturing from design has increased the speed of innovation. Before concluding, the paper looks at innovation in terms of the 'adjacent possible' in evolutionary analysis.

Keywords: Innovation, distributed knowledge, research location, reverse engineering, reverse innovation, frugal engineering, process innovation, adjacent possible.

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Introduction

With global production networks (GPNs), lead firms might carry out only branding, design and marketing, leaving all other tasks in production to numerous units around the world. This splintering of production tasks across firms has some important consequences for the development of production knowledge and for firms' upgrading possibilities, as GPNs' production knowledge is distributed across places where production segments are located. However, developing country firms need not be confined to the tasks they initially undertake in entering GPNs; they could also upgrade. The literature identifies forms of upgrading within GPNs as being those of process, function and product. But these upgrading trajectories are not linear: they involve learning and the development of national- and firm-level capabilities, often in the form of reverse engineering. They could also involve overcoming obstacles, as lead firms or first-tier firms try to prevent competitors emerging. Upgrading could also involve innovations. These innovations could be both in process and in product types.

The objective of this paper is to explore the role of innovations in economic upgrading within a GPN framework. Innovations barely get a mention in the GPN literature. As one analysis of innovations has pointed out, innovation has not entered into the GPN literature (Reddy 2011), although there are some exceptions, such as the papers of Dieter Ernst (2000, 2005). Consequently, this is an exploratory paper, trying to look at ways in which innovation enters into the GPN analysis.

The paper starts by looking at the manner in which GPNs distribute the use and location of knowledge. It then goes on to look at the possibilities for upgrading within GPNs, through processes of reverse engineering. We see that reverse engineering can itself include innovations, in both organizational and manufacturing processes. Recognizing that such upgrading is a matter not only of capabilities but also of firm-level strategies, we look at the firm-level conditions that might promote upgrading. Further, does the separation of design and marketing from manufacture, as occurs in the typical GPN, make a difference to the speed of innovation? This is the next question considered. Over the past decade, some product innovations have begun to occur in the set of developing economies called emerging economies, particularly China and India. What is the meaning of such reverse innovations, as they are called (Immelt et al. 2010), for the production of knowledge and technology? Besides the geography of manufacture, is there also the beginning of a change in the geography of innovation? Finally, we look at the distribution of types of innovation in terms of some formulations in evolutionary theory, using Stuart Kauffman's concept of the 'adjacent possible' (Kauffman 2000).

Splintering of Production and Distribution of Knowledge

In GPNs, there is a distinction between different types of firms in a production network. There is the lead firm, which undertakes the branding and marketing of a product, often also the design. What is important is that it governs the whole production network or value chain. Then come the Tier 1 firms that are the main suppliers, also often called 'full-package' suppliers. These are also often referred to as 'contract manufacturers'. They include firms that are contracted to undertake the manufacture of various electronic and computer products. Below them are various tiers of suppliers of components and services. Some of these production segments may extend from the formal to the informal sector, even into the household, where there is home-based production.

The division of labour within GPNs necessarily leads to a distribution of knowledge. Knowledge is both an input into and an output of production. Supplier firms in different production segments receive knowledge from buyers about specifications and processes. In the course of carrying out these production segments, they acquire this knowledge of the various tasks required. Specializing in carrying out a production segment, they may even gain additional knowledge about carrying out those tasks. For instance, a firm carrying out janitorial tasks is likely to acquire specialized knowledge in the course of carrying out these tasks. In a more complex manner, an IT service company providing financial analysis for various customers is likely to develop special skills in the technical discipline of developing software for financial analysis. As pointed out with regard to IT services, 'Continued work with global customers helped us improvise on processes in different geographies as we were able to see the commonality in these practices' (Pendharkar 2012). Outsourcing of tasks is then not only about benefiting from wage arbitrage but also about utilizing the economies of specialization, as specialized skills are developed in particular tasks.

There is a hierarchy of knowledge-intensity. The cut-make-trim (CMT) segment of garment production is relatively less knowledge-intensive than turning a design drawing into a detailed production system. The architectural design of an IT software system is more knowledge-intensive than the programming of parts of the software. Since there are larger numbers of persons in more regions of the world with low knowledge-intensive capabilities than high knowledge-intensive capabilities, tasks involving the former could be more easily outsourced than tasks involving the latter. The less knowledge-intensive a task, the more easily it could be outsourced. But not all knowledge related to production can be outsourced as easily or with equal efficiency.

The usual analysis of the spread of knowledge is that 'knowledge-intensive activities are more prone to agglomeration effects and hence resistant to geographic dispersion [as through GPNs]' (Ernst 2000: 12). But the development of GPNs inevitably leads to a dispersion of knowledge of production, as pointed out above. Further, whether it is in computing systems, electronics or even garments, the push to reduce costs leads to an outsourcing, even of parts of design. Manufacture of automobile components, for instance, includes substantial design activities. With the geographical spread of production facilities, there is also a migration of knowledge. As a result, electronic component manufacture also requires 'cross-functional, knowledge-intensive support services that are intrinsically linked with production' (ibid.: 16). This leads to the migration of knowledge.

For instance, manufacture of electronic chips has shifted to Asia. Since some extent of design interventions is required in solving production problems through incremental redesign, chip manufacturers in Korea, Taiwan, Malaysia and Singapore have been able to acquire some, possibly limited, design capabilities. While the supplier firm (and economy) acquires knowledge-intensive design capability, the lead firm may lose some of that capability. 'To the degree that the flagship [the lead firm] has moved to *global sourcing* … this implies an *erosion* of the *collective knowledge* which used to be a characteristic feature of the flagship's home location. In some cases, that collective knowledge may have migrated for good to the suppliers' overseas cluster(s)' (Ernst 2000: 17; emphasis in original). As a result, in order to solve production problems in their US plants, 'We [Texas Instruments] have to send our Malaysian engineers to solve their problems'(quoted in ibid.: 17).

What the above shows is that, with the distribution of production in GPNs,'the knowledge needed to create value is being increasingly dispersed, either in direct geographical terms, or in technological disciplines' (Foss 2006: 9) The number of knowledge nodes is increasing and firms need to tap them 'not just internally but also through an increasing number of alliances and network relations' (ibid.: 1).

The analysis so far points to the distribution of knowledge that accompanies the distribution of production by tasks in a GPN. Even knowledge-intensive tasks within the GPN could migrate, which may even lead to an erosion of such knowledge in the initial home country of the lead firm. In further analysing developments in the migration of knowledge, one could look at (1) the types of knowledge involved, for example formal/coded or tacit; (2) conditions under which lead firms adopt strategies of either passing on or restricting different types of knowledge; and (3) ways in which supplier firms increase their knowledge base either by 'learning by doing' or 'learning by training'.

Even if it is accepted that some forms of knowledge do migrate with production and are co-located with production segments, it does not follow that this leads to innovation. In knowledge along production segments, what is involved is knowledge in use. Some knowledge is created in the process, as firms acquire a better understanding of the tasks they perform. But this is still an activity of 'knowledge-using' rather than a 'knowledge-changing' type. Does the creation of new knowledge, whether of technology or of products, migrate along with manufacturing?

Production and Research Location

Innovation can occur in both final products as well as in intermediates, including production equipment and various other inputs into the final product. The objective of research and development (R&D) activities is to make innovations possible, innovations that may result in new products or in lowering the costs of existing products. These innovations may be incremental, in that they modify an existing product or production process. They may also be fundamental, in that they market a new product or radically change technologies. The innovation may occur in specific technologies, or they may be in general purpose technologies.

Right from Vernon's product cycle analysis (1966) onwards, there has been an assumption that, while production is likely to migrate in search of lower-cost advantages, the same is not likely to occur in the case of knowledge creation and innovation, which would still be located predominantly in the lead firm's home country. Economies of scale (possibility of using facilities for more than one research project), economies of agglomeration (clustering effects for knowledge externalities) and the interactive nature of innovation (requiring interaction between researchers and lead consumers) are some of the reasons given for R&D being more geographically sticky than production and thus innovation, which depends on R&D, being geographically less dispersed than production (Cantwell 1995).

This analysis was put forward by Patel and Pavitt, who held that 'the production of technology remains far from globalized' (1991: 17). The reasons put forward for such non-globalization were 'the primacy of multidisciplinary and tacit knowledge inputs, and the commercial uncertainty surrounding outputs' (ibid.: 18).

Tacit knowledge is, as they put it, 'person-embodied' rather than 'information-embodied'. This is better handled by physical proximity, which is also beneficial for the interaction with the market needed to cope with uncertainty. The first is a cognitive and the second a market-based reason for locating R&D and, thus, innovation in the lead firm's home country. This is modified only by the need for international presences and exchanges to take account of market diversity. This type of research activity, however, is merely adaptive, meant to modify products developed in developed-country markets for use in developing country markets.

There are, however, a number of developments that have occurred both in the nature of some current knowledge, and in the structure of markets, that change the situation from that analysed by Patel and Pavitt.[1] To take the second point first, the emerging markets are the ones that now account for a large part of global growth, whereas developed country markets are stagnating. In consumer electronics, the system developers that account for a major part of world demand for chips are located in Asia and cater to the Asian market. The large-volume consumer electronics markets of the Asian emerging economies are the main arenas for interaction between designers and lead users.

In the case of inputs, as in the case of chip manufacture analysed by Ernst (2005), manufacture is now concentrated in East Asia. Consequently, given the need for close interaction between design and manufacture, chip designers have found it necessary to shift their location to be close to the chip manufacturers.

Digitization and codification have had an impact on the nature of R&D. For one, they have reduced the element of tacit knowledge that was an important reason for requiring long experience in order to conduct research in mechanical and other engineering disciplines. The need for long experience to accumulate the necessary tacit knowledge gave an advantage to established centres of manufacturing. But as 'learning by doing' has been replaced by 'learning by training' (ibid.), the disadvantage of newcomers has been reduced. It has reduced the 'artisanal' nature of research (Reddy 2011). This makes it possible for

[1] The following analysis is based largely on Ernst (2005) and Reddy (2011).

newly developed centres, such as Korea and Taiwan, to enter into research and thus into innovation.

Digitization and the development of telecommunications (information and communication technology, ICT) have also made it possible to modularize research. This has led to the vertical specialization or vertical disintegration of research networks. Specialist houses can perform various parts of the design process, all of it integrated by the system company. 'Vertical specialization within GDNs [global design networks] is an attempt to provide an efficient and flexible organizational environment for the exchange of design knowledge across diverse design communities that are not co-located' (Ernst 2005: 64).

The impact of digitization and codification is not confined to chip electronics. It is also underway in software, telecoms, biotechnology and nano-technology. Conventional technologies also include electronics in their components: about 30 per cent of automobile parts are composed of electronics (Reddy 2011).

The growth of a large supply of relatively cheap trained and scientific persons in the emerging economies (particularly China and India) has also made it cheaper to shift whole research facilities, or parts of research, to developing countries. These centres may remain part of the Tier 1 company or flagship company's own facilities, but it still amounts to a geographical dispersal of centres of knowledge, with possibilities for 'reverse knowledge outsourcing' of the type referred to above in the case of Texas Instruments (Ernst 2005). Of course, the Tier 1 companies or flagship companies retain control of hard-core R&D and strategic marketing. However, the dynamics of GPNs point to the possibilities for the spread of knowledge nodes and the development of what in computer science is called 'distributed knowledge': knowledge not possessed by any single mind, but 'belonging' to a group of interacting agents, which emerges from the aggregation of the (possibly tacit) knowledge elements of the individual agents and can be mobilized for productive purposes (Foss 2006).

In the biotechnology and pharmaceuticals sector, perhaps more than others, as a result of distributed knowledge, collaborations have led to advances. A large biotech firm in the US, Chiron, is reported to have more than 1,400 informal and 64 formal collaborations. Its news release proclaims that, 'This network is a core strength of Chiron' (quoted in Powell 2002: 267). Overall, this capability is based on what is called the 'national innovation system' (Nelson and Rosenberg 1993).

Once some distributed centres are set up, initially because of low cost considerations, the concentration of technology production in these centres takes them beyond the advantages of low cost production.[2] They could emerge as new nodes of knowledge and technology creation. But the knowledge that is developed by the distributed nodes is a function not just of the access to knowledge but also of the 'possession of capabilities for utilizing and building on such knowledge' (Powell 1998: 269).

The result of these changes in the nature of R&D is that research and the resulting innovation are something that emerging country firms can enter into much earlier than before. Latecomers need not be confined to manufacturing while research and innovation continue in the home countries of the lead firms. As a result of innovating new technologies and products, former suppliers can now themselves become lead firms and establish their own GPNs. The Korean electronics firms, Samsung and LG, are prime examples of former original equipment manufacturer (OEM) suppliers becoming lead firms by taking the route of research and innovation. Another such example is the Taiwan–China firm HTC, which, from being an OEM supplier of mobile phones, has emerged as an independent lead firm (Sturgeonand Kawakami 2012). A key process in acquiring the knowledge to develop as a lead firm is reverse engineering.

Reverse Engineering

Reverse engineering is the process of making a product based on knowledge of that product. For instance, in a simple manner one might

[2] Salaries in, say, Bangalore or Shanghai are not only among the highest in India and China, respectively; they are even comparable with what would be paid to similar engineers or scientists in the US or Europe.

see a chair and then copy it. That would be reverse engineering. In a more complex manner, rather than just a copy of the original, there may be a process change, a process upgrading that could reduce the cost of production. For instance, one might know that statins have a certain chemical structure and the property of reducing cholesterol, but Pfizer has a patent for this product and so its costs are high. In a country where there are no product patents but only process patents, as was the case with India before its accession to the World Trade Organization (WTO), a pharmaceutical company with sufficient technical capability could find another non-patented process to manufacture the statin. This is the classic case of reverse engineering on the basis of which the Indian pharmaceutical industry built up its generic drug production capabilities in the heyday of import-substituting industrialization.

Reverse engineering does not exist just in currently developing countries. Japan used it extensively (Cosma et al. 2009) to catch up with Western manufacturing and to carry out redesign of products. The development of computer-aided design (CAD) has made reverse engineering simpler. 'Japanese success in new product development has led to reverse engineering being considered as a design process' (ibid.: 347). It is undertaken even in developed countries by latecomers. To give just some recent examples, the San Jose-based Phoenix Technologies in the 1980s reverse engineered IBM's BIOS (Operating System) to make IBM-compatible PCs. AMD reverse engineered Intel chips to make Intel-compatible chips (Schwartz 2001).

With the accession of almost all countries to the WTO and the spread of uniform laws for protection of intellectual property rights (IPR), such reverse engineering has presently become less possible.[3]

[3] This is not to mean reverse engineering has ceased to exist. It exists even in high-income (that is, Organisation for Economic Co-operation and Development, OECD) countries, with all their IPR legislation. For instance, the Windows operating system of Microsoft bears a clear resemblance to the Macintosh icon-based and pull-down operating system. Currently, Apple is engaged in an all-out war against Google's Android mobile phone operating system, which it claims to be a copy, or reverse engineered.

Rather, the spread of production knowledge occurs through the insertion of firms and countries into parts of GPNs. To some extent, as lead firms outsource more functions, there is a transfer of technology. The development of supplier or contract manufacturer's capabilities could also come about through co-evolution, whereby the lead firm and contract manufacturer together develop the required technological packages and solutions (see Sturgeon and Lee 2001, quoted in Sturgeon and Kawakami 2012). But upgrading within GPNs often involves reverse engineering.

Reverse engineering is not just a copycat activity. It often involves many process innovations that reduce production costs. AMD reduced the cost of Intel-compatible chips (Schwartz 2001). Indian pharmaceutical companies' reverse engineering also changed the processes involved. This was done in order to get around process patents, but they also involved cost reductions of as much as 30 per cent (Athreye and Godley 2009). In the case of reverse engineering the drug for chronic myeloid leukaemia, the use of computer simulations reduced production costs from INR 1,000 to just INR 90 (Reddy 2011). Of course, the low price resulting from side-stepping patent payments through generics is likely to have been the major consumer benefit, more than the reduction in production cost.

Advancing into being lead firms with global GPNs does not have to be confined to firms that start as suppliers or contract producers. Suppliers have an advantage over independent producers in that they become aware of the quality and design requirements in carrying out their input supply functions. But independent producers can also take the route of using R&D to master new technologies and carry out innovations. The Chinese telecoms equipment manufacturers Huawei and ZTE are examples of global lead firms that developed from independent manufacturers by using R&D extensively both to carry out both reverse engineering and establish their own proprietary technology products.[4] The Indian auto manufacturer, Tata, is another example of an independent manufacturer that has used innovation to

[4] See Fan (2006) for an analysis of the role of innovation in establishing the Chinese telecoms equipment manufacturers as global players.

become a lead firm, an automobile assembler with its own GPN structure. Thus, there are examples of both GPN suppliers and independent producers taking the route of innovation to establish themselves as lead firms. It would be interesting to study the relative constraints and opportunities facing these two sets of manufacturers: GPN suppliers and independent producers.

But particularly in consumer electronics, there has been a development of what is called 'co-evolution' (Sturgeon and Lee 2001, quoted in Sturgeon and Kawakami 2012). In electronics, the buyers retained their core competence (product design and marketing) while shedding non-core functions to suppliers. Supplier firms have been able to upgrade their capabilities within GPNs. This has often involved taking up functions, such as design, at the behest of buyers. Both buyer and supplier firms could together take up development of design and fabrication, or the route of co-evolution (ibid.). But there is still a large jump from being OEMs or even original design manufacturer (ODMs) to becoming original brand manufacturer (OBM) firms. The design, branding and marketing of final products require capabilities that are not developed by having manufacturing capabilities. But co-evolution in the electronics industry, by outsourcing the detailed design work to suppliers, certainly made it easier for suppliers to move from being OEM firms to being OBM firms. This might account for the fact that the Korean firms, Samsung and LG, or the Taiwan–China mobile phone manufacturer, HTC, initially OEM and ODM suppliers to major Western brands, moved quickly into developing their own brands and becoming lead firms. Since in consumer electronics suppliers are part of the technology development, if not initial design architecture, process, co-evolution substantially eliminates the need for reverse engineering.

Sturgeon and Kawakami (2012) mention the constraints that supplier firms in electronics GPNs face in upgrading and the strategies they follow to overcome these. The latter include acquisition of declining brands and separation of branded products manufacturing from contract manufacturing. The point we would add is that reverse engineering is an important part of the strategies of suppliers to overcome the constraints put in place by lead firms. Of course, lead firms and the developed economies in which they are located have responded to such competition with tighter IPR protection laws. This, as Ha Joon Chang characterizes it is a policy of 'kicking away the ladder' to inhibit upgrading by supplier firms and developing economies.

Process Innovation

Process upgrading is seen as a matter of moving from one type of current production organization to another, but known, method of production organization. It could involve the move from artisanal to assembly-line production, with concomitant reductions in cost. But process upgrading can also mean a change from an existing method of production organization to fashioning a new method of production organization, one that did not already exist. The introduction of Fordist mass production through the assembly line was one such innovation in its time. So too was the Volvo–Toyota quality circles, which reorganized the traditional assembly line to build work teams.

In the GPN system, there have been innovative changes in the organization of production, a process upgrading as it were. An example of a process innovation is the global delivery model (GDM) for software services pioneered by Indian IT companies. Modularization and uniform protocols made it possible to have a software service split up into and carried out in a number of locations. This allowed the IT companies to utilize the global segmentation of the labour market, using a few higher-paid professionals on-site, along with lower-paid professionals off-site, basically in India. Location in more than one time zone also allowed the work of producing the service to be carried on a 24-hour basis, as work followed the sun. This reduced delivery time. This organization of work, the GDM, reduced costs in two ways, by utilizing labour segmentation and by reducing delivery time. It was the basis of the Indian IT companies' cost advantage in the supply of software services. It was a disruptive innovation, in that it changed the manner and cost of delivering software services. But business process innovations can be copied and spread through the industry. In order to retain markets, the global IT majors, such as IBM and Accenture, were also forced to adopt the GDM system as they set up offices in India and other low-cost centres to combine with their high-cost home-country offices.

There are likely to have been other such process innovations in GPNs. One possible candidate for such a process innovation is that of garments' supply-chain management, pioneered by Li and Fung. The newer development of supply-chain cities could be another case for study of process innovations in the organization of production in GPNs. Dongguan of Luen Thai Holdings is a garments' supply-chain city. Not only are input requirements available, but also designers from the buyers (e.g. Liz Clairborne) are located on-site. All this should reduce time to market. The Chinese supply cities could have process innovations that are worth studying.

Path Dependence and Firm Behaviour

Some of the new knowledge centres, although geographically dispersed, still remain under the ownership or control of the lead companies. For instance, Texas Instruments and other US corporations' research centres in India are acquiring a growing number of patents. Their geographical source is India, but their ownership is with the US corporations (Mani 2009).

The question does arise: When lead, developed country, firms can take up original software creation in India or China, why can Indian or Chinese firms not do the same? The reasons are different from Kaplinsky's (2005) 'immiserizing' dilemma of being caught between the rock of oligopolistic buying and the hard place of competitive selling and, thus, not having any room to manoeuvre. One problem is that the market for high-tech products is located largely in developed countries. To penetrate into these markets, firms of developing countries require in-depth market knowledge, something that can come only through long exposure to developed countries' markets. Second, establishing a brand demands not only deep pockets but also risk-taking aptitude and capabilities. A firm can get comfortable with its high earnings from its position in a segment, and thus have no reason to go into new and difficult areas. There is, in a sense, no 'push' for a firm to change its business model or activities if it faces no challenge in its existing model and activities.

Indian firms in IT services (Infosys, TCS and Wipro) now have annual billion dollar (US) net revenues and could well invest parts of this in the creation of new, proprietary software. They, and other smaller firms, have made some moves in this direction. But the dynamics of their own business models, the ones that have given them success so far, could push them to invest their revenues in further expanding their network of IT services. In fact, from providing parts of software services, they are now trying to offer 'end-to-end' solutions in order to compete with the likes of IBM and Accenture. What offering end-to-end solutions means is that the company will carry out not only the coding or programming and maintenance of the software but also its conception and design. These early parts of the value chain, conception and design, are often the areas where more of the value added can be captured. The pricing system for the whole service itself changes, based not on what the cost to the supplier is likely to be but on what it is likely to mean for the buyer.

Similarly, Indian firms in pharmaceuticals have made a success of generics production, which is really a form of reverse engineering. They have built successful business models based on the production of generic drugs through reverse engineering. But they are also attempting to get into the R&D involved in new drug production, along with other bio-pharma start-ups, such as Biocon. Or, as in the case of Ranbaxy now, by attempting to become part of a global lead firm, Japan's Daiichi.

High profits earned with a business model that maximizes income from a segment of production results in what is called path dependence. If path dependence makes it difficult for Indian producers in low-tech industries, such as garments and leather products, to get away from the small-scale unit with informal labour contracts system of production, it also inhibits India's successful firms in IT services and pharmaceuticals from breaking into the new ground of creating proprietary products in software or new drugs. What kinds of economic situations force firms to break from path dependence and attempt to become lead firms—this is a very large question of economic development, related to both constraints and opportunities.

The one point we would stress here is that firms will break from a path when their earnings, measured in whatever manner, come under threat. When margins fall or rates of growth slow down, then there are likely to be attempts to change the paths of firms' activities. In a way, this then becomes the reason for attempting innovation. This innovation could take a number of forms—the movement, as with Indian IT firms, from concentration on specific software services to providing end-to-end solutions for particular industries, or verticals, as they are called. It could also take the form of developing new products. We now look at the specific factors influencing the nature of innovation in the emerging economies.

Frugal Engineering in Emerging Economies

The emerging economies, or rather India and China within this group, because of their large populations, have economies that are large even at substantially lower per capita incomes than in the advanced economies. India, even more than China, has a generally low-value but high-volume market. This is what Prahalad (2006) referred to as the 'bottom of the pyramid'. Though a low-value market, the high volume makes it a target for market expansion. This large market then affects the nature of market-based innovations, which attempt to design specifically for this high-volume, low-value market segment. As manufacturers in emerging economies, or even those from developed economies attempting to serve emerging markets, try to develop specific products for this important market, they carry out innovations in production processes.

This changes the traditional sequence of innovations. While formerly innovations were first carried out in developed economies and then adapted and spread to developing economies, in the emerging economies, as we see in the examples given below, endogenous innovation systems have appeared to cater specifically to the high-volume, low-value markets. Rather than adapt or strip down developed country products for poorer economies, what reverse innovation involves is often a change in the operating systems to make the product cheaper. Of course, this is still just a process innovation, and not a new product as such.

The characteristic form of these reverse innovations is what is now being called 'frugal engineering', a term attributed to Carlos Ghosn, former CEO of Renault (Gomes 2011: 1). Frugal engineering economizes on use of materials and energy in the production and use of a product. India and China, in particular, seem to have become home to frugal engineering, though other countries with relatively high-volume but low-value markets, such as Indonesia, are also involved in the process. The reasons for India being a leading base for frugal engineering may be (1) the long history of import controls, which have forced Indian firms to manage with limited supplies of scarce and costly materials, (2) continuing energy shortages and (3) the earlier IPR system, which provided only process and not product patents.

Frugally engineered products have been produced not only by Chinese and Indian lead firms but also by OECD multinationals. For instance, GE's Indian branch produced the MAC4000 handheld electro-cardiogram machine; GE's China unit produced the PC-based ultra-sound machine; Nokia in India produced the 1100 mobile phone. GM in China designed the Chevrolet Sail, as a low-cost passenger car.

Some of these products are the result of tinkering. This is so with the NeoNurture baby incubator, designed in Indonesia by the MIT (Massachusetts Institute of Technology) Design that Matters team (Johnson 2010). This incubator was made out of car parts, a sealed beam headlight for warmth, dashboard fans for filtered air circulation and door chimes for alarms, all powered by a standard motorcycle battery.

But many frugally engineered products are the result of changing the basic operating principle. The IIT-Madras design team (see TENET 2012; Vortex Engineering 2012) made a cheap ATM usable in low-volume markets. Instead of the standard spring-loading mechanism for dispensing notes, they fashioned a gravity-loading system. Instead of expensive switches and dedicated communication lines, they used the village internet kiosk. All this reduced the cost of the rural ATM to just 10 per cent of that of the standard ATM. Further, it reduced power requirement by 90 per cent through solar panels. Such a low-cost ATM is suitable for rural markets, where the volume of business will be quite low. They can also be used in off-grid locations. They are now being installed by the State Bank of India in rural branches in India and also being sold for installation in Africa.

The well-known Indian pharmaceutical companies in reverse engineering also changed the processes involved, resulting in a 30 per cent reduction in cost of production (Athreye and Godley 2009). The Tata 'Swach' water filter uses nano-silver particles, and 14 patents have been filed around this technology (Ramadorai 2011). Tata's Nano has also re-engineered many parts of the car. Its relative inexpensiveness relates to the materials used for the body and engine parts. As many as 37 patents have been filed to cover the engineering innovations in the car, while the Nano's 'Powertrain' design has another 34 patents (ibid.).

For the Nano, the electronic control unit (ECU) was completely redesigned. As the chairman of Bosch's automotive division put it, 'Normally we would adapt the products we use on premium European cars for use in the Indian market. And if our goal is to take 10 per cent out of the cost, we can do that with "value engineering". But if your goal is to take 60 or 70 per cent of the cost out, you have to start from scratch' (quoted in Freiberg et al. 2011: 154). The result is an ECU that can now be used by Bosch and Tata in other applications.

GE China's PC-based ultra-sound completely redesigned the architecture of ultra-sound machines (Immelt et al. 2009). It was based on a laptop with sophisticated software and the cost was barely 15 per cent of the high-end ultra-sound machine. Of course, some functions are not available in the China model. But the important point is that the China model was based on sophisticated software taking over many of the earlier functions in more expensive hardware.

Frugal engineering, as the above examples show, is high-tech but has the objective of reducing the overall costs of the product. Frugal engineering is currently the specific form of innovation in emerging economies. It reduces both material and energy costs and is based on bringing down both initial and operating costs to meet the price point requirements of low-income markets.

Reverse Innovation

But is frugal engineering meant only for low-value markets? In the end, buyers will beat a path to the maker of the legendary cheaper mousetrap, in the sense that, for a standard product, the cheapest will prevail in the market. With all budgets under stress, there will be a need to reduce costs over time. Under the current economic crisis, incomes in developed countries are under pressure and there is likely to be a market for cheaper products (Sturgeon and Kawakami 2012). The US government is also trying to reduce healthcare costs, so GE is marketing both low-cost ECG and ultra-sound machines, developed in India and China, respectively, in the US. The US Post Office has purchased the electric version of Tata's Acer, a small truck (Freiberg et al. 2011). Consequently, these techniques of frugal engineering are not just innovations for emerging markets, but can also be *reverse innovations*. Earlier on, products were designed for developed country markets and then pared down to be sold in developing countries; innovations were made in the developed economies and the products adapted for local conditions in developing economies. But with the new round of frugally engineered products, the innovations are being made in emerging economies and then could be, and are being, re-exported to developed economies. This is the reversal of the traditional innovation mode that has held since the Industrial Revolution.

Emerging economies are becoming centres of innovation in many fields—low-cost healthcare devices, solar and wind power generation systems, bio-fuels, cheap and electric cars, low-cost homes, etc. Why is innovative work in these areas being located in emerging economies, with high-volume but low-value markets? The new aspects of present-day globalization need to be highlighted, as they have created ground for wide-ranging reverse innovation. First, with the spread of telecommunications and particularly of internet consumption, developing countries are also well aware of new products and there is a demand for them, albeit at a fraction of existing developed country product prices. With large countries such as China and India entering the global economy, this has translated into tens, even hundreds, of millions of customers, something that did not happen earlier. On the supply side, even at a much lower level of per capita income, these countries have entered into high-tech R&D because they can afford the high initial cost in R&D, and they have also created a large supply of high-tech engineers by dint of their large size (Altenburg et al. 2008).

All of this means that in these emerging economies there is scope and pressure to extend into the area of feasible technologies that economize on use of materials and energy and provide low-price products for these large markets. This is a market-driven process whereby existing knowledge is used to re-engineer products on a frugal basis, reducing both material and energy intensity and cost. What probably increases in these cases is the knowledge intensity of products, with software taking over many earlier core hardware functions, as in the case of GE's China-based ultra-sound machine. The emerging economies not only provide a demand for such frugally engineered, products, they also have the technological and engineering capacity to carry out the necessary reverse innovation.

Their increasing technological capacities are reflected in their rising shares of global patents and designs, much more so for China than India. Although patent filings are not even across countries, China overtook the US in 2011 with 24.8 per cent of global patent filings, as against 23.5 per cent for the US. The share of middle income countries as a whole increased from 25.2 per cent in 2008 to 33 per cent in 2011. Of course, the major contribution to the middle-income share is that of China. But India, though far behind, is second to China among middle-income countries and increased its number of patent filings by 11.2 per cent in 2011, as against China's increase of 33.4 per cent (WIPO 2012a). Indians, whether located in India or elsewhere, account for 13.7 per cent of international patent filings (Ramadorai 2011). Reflecting the rise of China, the two major Chinese telecoms equipment manufacturers, ZTE and Huawei, were the first and third companies (with Japan's Panasonic in between in second place) filing patents.

These changes led the director-general of the World Intellectual Property Organization (WIPO) to state that 'even though caution is required in directly comparing IP filing figures across countries, these trends nevertheless reflect how the geography of innovation has shifted' (Gurry 2012, Foreword in WIPO 2012b).

Since the emerging economies provide the strongest demand base for cheap products, it is in these economies that we would expect to see the greatest efforts to design products that are frugally engineered. If the developed economies provide the economic system in which new advanced products are more likely to be developed, the emerging economies are the economic system in which frugally engineered products are more likely to be innovated.

Reverse innovation with lower prices also means the products now being developed and sold in emerging markets would definitely come back to be used in developed economy markets, particularly in lower-price market segments. The possibility of cheaper products being exported to developed markets makes it important for lead firms in developed countries to try to be part of the reverse innovation process itself and not leave it all to emerging country firms. As the CEO of GE put it, 'To be honest, the company is also embracing reverse innovation for defensive reasons. If GE doesn't come up with innovations in poor countries and take them global, new competitors from the developing world—like Mindray, Suzlon, Goldwind and Haier—will' (Immelt et al. 2009: 5).

In a low-income economy, only techniques that are frugal will be able to utilize the possibilities presented by large but low-value markets. Thus, there is likely to be more effort put into solving the relevant problems in frugal engineering. On the other hand, in a high-income economy, such economization is less required. At a broader level, one may say that the level and manner of social and economic development influence the manner in which problem solving is approached. It sets the cost and price parameters within which solutions have to be found.

Limits to Reverse Innovation

The above advances in technology are all based not only on existing knowledge but also on technology that is more or less already there: techniques possibly used for some other purpose, but still already there. In a sense, they are incremental changes in technique. In the terminology of Lester and Piore (2004), frugal engineering is basically of an analytical, problem-solving type.

There are at least two kinds of innovations that are not matters of analytical, problem-solving approaches—the development of new products and of new technologies. The first could well be related to per capita income. Higher per capita income economies are more likely to be able to accept new products and develop new ways of consuming. In this, the low per capita income countries would in fact be at a disadvantage.

Further, innovation of new products requires close and repeated interaction between producers and users, or, more accurately, 'lead users' (von Hippel 2005). These lead users may be individuals, as, for instance, those who ride mountain bikes and have an idea of the varied qualities required in different terrains (Bijker 1997). Or, they may be manufacturers or producers. For instance, Intel, the chip manufacturer, interacts regularly with both software producers, such as Microsoft, and computer manufacturers (Lester and Piore 2004). This interaction is essential to both design and subsequent marketing. Economies in which interactions between product developers and lead users are denser are better placed to develop new products as compared with economies where such interactions are substantially less dense. On this count, developed economies with more lead users are likely to fare better than emerging economies.

However, the global nature of businesses from the emerging economies puts the emerging economy firms in touch with developed market requirements. Besides, the development of the internet makes interaction denser, reducing the effect of distance. But one would expect that developed economies would still have a lead over emerging economies in this respect. Or, to put this in another manner, firms from developed economies, OECD economies, are more likely to be in touch with the market requirements of these economies. The R&D work could well be carried out in an emerging economy, but this would be by subsidiaries of the multinational corporations (MNCs) from OECD countries, For instance, the Korean Samsung has some of its major research units in India. These units are involved in high-tech product development that has enabled Samsung to be the major competitor of Apple. For instance, the Indian units developed the gaming, music, reader and social networking apps available in Samsung smartphones and tablets. China, too, is host to major R&D units of various MNCs: Microsoft, CISCO, GE and GM, among others. Of software outsourced by Japanese companies, some 80 per cent is carried out in China (Reddy 2011).

Where close interaction with high-income customers is required, corporations from the developed economies concerned would have a lead over those from emerging economies. However, with emerging economy corporations themselves operating in most or many of the developed economies, as is true of Indian IT companies and Huawei, the Chinese supplier of telecoms equipment, corporations from the emerging economies are also in a position to reduce existing gaps.

The technology creation gaps are also being closed by emerging economy firms setting up research centres in developed countries, mirroring the moves of developed country firms that have set up research centres in emerging economies. Indian pharmaceutical companies have set up research centres in developed countries. For instance, Dr. Reddy's has a research laboratory in Atlanta, US, which in seven years obtained twelve US patents. Wockhardt first set up a joint venture with Rhine Biopharma in Germany, and later took over full ownership. Rheine Biopharma successfully developed the hepatitis-B vaccine, Biovac-B. Wockhardt also bought up Esparma, with nine international patents and ninety-four trademarks (Athreye and Godley 2009).

Making the change from providing offshore services to making new products or undertaking end-to-end consultancy, however, is a big leap, requiring a change in the business model of the company concerned. Indian software service providers have been comfortable with a diet of high-margin service provision. The onshore–offshore process they have developed has enabled them to outcompete IBM and Accenture in the provision of services. However, it has in turn led to two developments. First, since the innovation of the Indian software companies was a process innovation, others could copy it. On the one hand, numerous small Indian and other developing economy firms (e.g. in the Philippines) have emerged as competitors in an increasingly commoditized service delivery system. This increased competition has brought down margins for the Indian software majors. On the other hand, the global players, such as IBM and Accenture, have also copied the onshore–offshore service provision process.

The resulting shrinking of the margin has forced a change in the business model of the Indian IT companies. The three major companies, TCS, Infosys and Wipro, have all moved to change their business organizing from different service divisions to what are called 'verticals' or industry divisions. These industry verticals aim to provide end-to-end or system-integrating consultancy services to global clients.

But Infosys has also taken up the task of linking consultancy with technology product development. While enabling it to move into high-value technology consulting, this will also enable Infosys to reap the benefits of products originally designed as customized technology to solve certain business problems, but later developed as products integrated into full service provision. Infosys is in the process of developing its technology products division, which already has Flypp (for Aircel and other telecoms providers) and, most famous so far, Finnacle, the widely used banking systems software. More recently, it has introduced the 'mobile wallet' product now being used for the Airtel mobile money system. 'One of our strategies is to push our products and platforms. Today, we have nine platforms with twenty-two clients, one of the platforms has reached double-digit clients which means you are deriving ten times revenue for a single investment' (Shibulal 2012). Tata Consultancy Services (TCS) has developed the Diligenta accounting platform, besides its earlier BaNCS banking platform, on both of which it has IPR (Shinde 2012). Another Indian IT major, Cognizant, has also taken up such a technology-centred and thus product-creating approach, going beyond service provision.

Products do emerge out of consulting assignments, as the consultants try to design solutions for the problems they face. For instance, TCS, in the course of developing an IT system that could work with a variety of computers, developed a Local Area Network (LAN) system. But the LAN was seen just as the solution to a particular consulting problem and not as a product in its own right.[5] Eventually,

[5] Keshav Nori, former Head of R&D, TCS, personal communication.

it was Norton and not TCS that developed and marketed the LAN. What this shows is that it is necessary to have a different business focus in order to turn customized solutions that emerge in consulting assignments into marketable products.

The Chinese approach to technological innovation has been characterized as 'innovate by commercialization, as opposed to constant research and perfecting the theory, like the West' (Wale 2012). This involves a number of rounds of commercialization 'to get an idea right, whereas in the West companies spend the same amount of time on research, testing, and validation before trying to take products to market' (ibid.).

Innovation through commercialization has resulted in numerous innovations in domestic consumer electronics, instant messaging and online gaming (ibid.). More important from the point of view of technological development with global marketing implications are Chinese advances in telecom equipment manufacture (Fan 2006), and more recently in the wind and solar power industries and high-speed rail transport.

What about major changes in technology—the development of what are called 'general purpose' technologies, such as the steam engine, iron and steel and then electricity and fossil fuel technologies, inorganic chemicals or IT? Innovations in these areas might require a very different kind of analysis, not related to global value chains (GVCs) or GPNs. This is something we will not go into here, except to say that, because of the large expenses involved and the very substantial externalities that could transform ways of living and working, such advances in general purpose technologies might require a manner of industrial policies for their development. Further, they are also related to advances in the sphere of knowledge, not only of basic scientific knowledge but also of the transformation of that knowledge into technology. Both of these require high levels of scientific capacity, something in which China, more than India, is catching up with the major powers. Chinese advances in wind and solar technology, as well as high-speed rail transport, could be important in the newly developing general purpose technologies.

These advances in knowledge and technical ability also have substantial public goods characteristics. Not only would the investments for developing such technologies be large, but also, when developed they would transform the ways of living and working. Nano technology is one such technology that could be developed. The large investments and the public goods character both would require 'deep pockets' of the kind that governments can deploy. In a sense, they require a manner of industrial policy, based on choosing particular technologies for development (Applebaum 2011). China, for instance, has put in enormous effort into developing nano technology and renewal energy technologies. The whole development of the internet itself was the result of US government, specifically Department of Defence, spending. Thus, innovation in general purpose technologies would require more than just market-reacting developments of technique. It is another major step from frugal engineering to developing new technologies, or even new products.

At the same time, there is an important role for the market. We cannot know in advance which particular approach will be the one that will ultimately prevail. A recent example of a failed state decision is that of the Korean government's insistence on Korean telecoms companies adopting the Samsung WiBro system (EIU 2011). This later had to be abandoned, as operators shifted to 3G systems, meaning that telecoms operators incurred unrecovered costs. The Chinese government too supported certain initiatives that were not successful, such as the development of a 3G telecommunications protocol called TDS-CDMA and replacing the global Wi-Fi standard with a Chinese internet protocol, WAPI (McKinsey 2012). Competition rather than state-sponsored support of 'champions' is needed for the purpose of choosing technologies. Consequently, a policy of state provision of public goods needs to be combined with market-based competition among innovators.

The development of new products and new technologies depends on the advance of knowledge and its use in what Lester and Piore (2004) call the 'interpretive mode'. This depends vitally on a conversation between scientists, technologists and potential or actual consumers (lead consumers), conversations that are developed in public spaces, such as universities. These public spaces are under challenge even in developed countries, as private spaces are developed in universities working for defence or private company contracts.[6] However, there is little doubt that these public spaces are much more advanced in the developed economies, and the emerging economies will need to catch up in the quality of such public spaces. Of course, the internet makes inter-country conversation much more possible than it was earlier, but there is still a lot of catching up to do, both in the general quality of education and in specific scientific research.

High-speed Innovation

One factor stands out in the contemporary scene: the high speed of innovation. Some of this owes it to the speed of technological change in some key areas, such as the well-known case of computer chips. But a factor to be considered is that of the impact of the splitting-up of manufacture into design, largely still concentrated in lead firms in developed countries, and the outsourcing of manufacturing in developing economies, largely in Asia. What this splitting-up of the production system and the separation of design from manufacture does is reduce the sunk costs that an integrated design-cum-manufacturing enterprise would necessarily incur in turning innovations into marketed products. With this separation, the sunk costs are all on the side of the manufacturer, the designer, the lead firm, incurs none of this. The result is that the lead firm, concentrating on design, is not constrained by having to amortize and secure adequate returns on its fixed capital. It need not be inhibited in replacing a fairly recent product with a newer one.

Apple is a quintessential example of a lead firm where design is separated from manufacture. Apple prides itself on integrating both software and hardware, but the truth is it integrates software with the design of hardware. The hardware itself is manufactured by contract suppliers, such as Foxconn.

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[6] This point was suggested by John Pickles.

The spread of manufacturing capability across Asia means there is competition among actual and potential suppliers, which would mean that the suppliers' prices would be at the competitive level, with little of the surplus profit Apple is able to gain from its own monopoly position. From the point of view of the speed of innovation, what the separation of design from manufacturing means is that the amortization of sunk costs does not enter into Apple's calculations in introduction innovations. As pointed out, 'The most successful [innovators] aren't afraid to cannibalize their big revenue generators to generate new business' (Ante 2012). Specific mention is given to Apple's I-Pod, then the I-Pod Touch, followed by the I-Pad. Each of these products quickly followed the earlier one, and cannibalized the earlier product, taking over parts of the older product and adding new features. This is relatively unusual business behaviour, such that we would attribute to the fact that sunk costs in manufacturing do not need to come into Apple's calculations. Apple, in a sense, has become a pure design and marketing company, similar to the big clothing and shoe retailers.

Before concluding this note, we consider how we could look at technological innovation in an evolutionary framework. This could not only help explain why emerging economies are the source of frugal engineering but also provide a framework for analysing innovation in an evolutionary manner.

Innovation and the Adjacent Possible

Technological innovations extend the range of actually existing techniques. Innovation extends the actual into what Stuart Kauffman termed the 'adjacent possible' (2000: 45). In the biological sense in which he originally defined the term the adjacent possible is the set of 'molecular species that are one reaction step away from the actual, but do not yet exist' (ibid.).

In an economic sense, the actual is the set of techniques that exist, but there is also a set of techniques: all those that are feasible with the existing set of knowledge. As Joel Mokyr characterizes the relation between knowledge and technique, 'The mapping from the set of useful knowledge (omega) to the set of feasible techniques (lambda) must be one of the central notions in any evolutionary model of technology' (2000: 54).

But besides the set of feasible techniques, there is also the set of actually existing techniques; let us call this sigma. The set of feasible techniques minus the set of actual techniques (lambda–sign=epsilon) would then correspond to Kauffman's 'adjacent possible'. We could define the adjacent possible of the world economy as being the set of feasible techniques that do not yet exist, epsilon. Obviously, the set of feasible techniques is constrained by the set of useful knowledge, but the actual techniques do not completely fill the space of feasible techniques, thus allowing for an expansion of the economy into the 'adjacent possible', even with the existing state of knowledge.

Kauffman uses the analogy of Lego constructions to characterize the adjacent possible of the 'econosphere' (as he terms the global economic space). But not all possible Lego combinations are feasible. The set of feasible Lego combinations is limited by the state of existing knowledge. Thus, at any time, given the existing knowledge, there are only a certain number of Lego combinations that are feasible. Of course, not all of the feasible Lego combinations (or technologies) have in fact been created. And the set of feasible Lego combinations keeps increasing over time, as scientific knowledge increases. The former is the set of actually existing technologies, or sigma; the latter is the set of feasible technologies at any point of time, Mokyr's lambda; the adjacent possible is [lambda–sign] = epsilon.

But what determines the movement into the adjacent possible, determines which feasible technique will be taken up? Here, there is a twofold determination. Initially, there is the hunch of the technologist and the firm of what will work and what will be marketable. But, finally, there is a market determination of what feasible technique actually holds its own in the market.

What this means is that movement from the actual to the adjacent possible is not random. It depends on the decisions of innovators and firms on the basis of their understanding of needs and opportunities, on market factors. It is very context-dependent and can vary from one market to another, specifically from high- to low-value markets. In a high-value market, it may not be important to pay attention to unit price; the features of a product are likely to be more important. But in a low-value market, price and operational costs may be more important than certain additional features. Different market segments (high value, low value) may be thought of as different peaks in 'fitness landscapes' in the evolutionary sense. As a result, traits or techniques not selected in one peak of the fitness landscape may be selected in another peak of the fitness landscape.[7] The existing economic system determines the nature of the peaks in the fitness landscape. In relatively low-income markets, the low-price but high-volume nature of the market would lead to the selection of the relevant frugal product; in a high-income market, the high-price product with elaborate features, giving high returns but low volumes, would be selected.

Thus, the manner in which the adjacent possible is approached would differ between firms operating in different markets. For an OECD market, it would not be necessary to design, say, a refrigerator that can work with a power breakdown, but that would be important in the fitness landscape of rural India or rural Africa. These fitness differences mean that firms operating in different market segments will approach the adjacent possible in different ways. The adjacent possible would be used by firms in low-value market segments to find ways to reduce both product and operational costs, while making products with basic functions; firms operating in high-value segments would look for features that would add value to the product.

These differences between these market types or peaks in fitness landscapes could mean that 'developing country firms may have an advantage in designing and making products for low-income markets as they have a better understanding of these markets' (Staritz et al. 2011: 5), But, as pointed out by Immelt et al. (2009), products developed for low-income markets may come back to capture markets in high-income countries too. Not all market segments in a high-income

[7] See Mokyr (2000) and Perkins (2000) for use of the concept of 'fitness landscape' in the analysis of technological innovation.

country are high-income markets; there are also low-income markets in high-income countries. In addition, the ongoing downturn has 'introduced a new cost-consciousness among consumers in developed countries' (Sturgeon and Kawakami 2012: 291). As a result, the cheap Android-based smartphone developed for markets in China and India is now capturing low-income markets in the US. Frugally engineered products emerging from research in low-income, high-volume markets may not remain confined to these low-income countries.

Conclusion: Product upgrading and innovation

The GPN literature distinguishes three forms of upgrading: process, function and product. Product upgrading refers to improvements in the operation or design of an existing product. Such improvements in design or operation could be of different types, depending on the nature of the markets being served. With emerging economy markets, particularly those of India and China, being of the low-value but high-volume type, there is scope and pressure for the development of products that economize on both material and energy use. These go beyond catch-up industrialization and are the beginnings of innovation. Frugal engineering of products is the manner in which innovation is characteristically taking place in emerging economies. Since such innovations take place in the emerging economies, even if they are carried out by developed country lead firms, they have been termed reverse innovations.

What this means is that the division of labour within GPNs has not remained static. A brief look at history after World War II shows that there has been upgrading and even development of lead firms by countries that were initially somewhat lower down the GPN hierarchy. In the immediate post-war period, Japan took up the bottom rung of manufacturing, but then graduated to higher status, vacating the lower positions for the then newly industrializing economies (NIEs) of Korea, Taiwan, Singapore and Hong Kong. In the 1980s and 1990s, these NIEs themselves graduated up the chain and the bottom rungs were taken up first by the Southeast Asian countries and then by China. This sequential upgrading (Ozawa 2009) is an important part of the dynamic of contemporary GPN analysis, distinguishing it from the relatively inflexible division of labour of dependency theories. The possibility of using integration in GPNs to grow into lead firms and develop into leading players is an important issue in analysing the possible development trajectory of the emerging powers.

This paper has argued that the role of developing country firms as suppliers is not just restricted to receiving technology and learning how to use it. Besides knowledge-using, developing country firms also undertake knowledge-changing capabilities (Bell and Albu 1999). Knowledge-changing enables both catch-up through reverse engineering and innovation, which in turn are part of the creation of lead firms from emerging countries. All this, however, is not just a matter of firm-level or even industry-level capabilities, but depends crucially on national scientific and innovation capabilities and incentives.

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