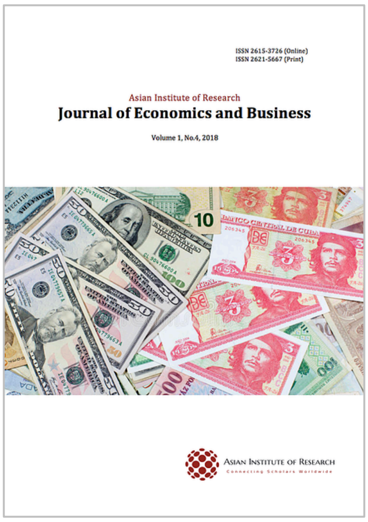

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Graphene Revolution: An R&D-Based Growth Model Interpretation

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Abstract
In the physics community, there is a new nanomaterial known as graphene which has been invariably referred to as the disruptive technology arguably due to its capability to revolutionize the information and communication technology. In the economics community, there is a celebrated model of economic growth which has been termed the R&D-based growth model due to its stipulation that growth is achieved through creative destruction, an idea introduced by the late economist Joseph Schumpeter. Inasmuch as the idea of disruptive technology is akin to that of creative destruction, this paper explores the extent to which the so-called graphene revolution can be given an R&D-based growth model interpretation. Although such consistency exists, there are some discrepancies which may alter the conclusions of the model.

Keywords: Graphene, R&D-Based Model, Economic Growth, Technology Progress, Human Capital, Endogenous

1. Introduction

The idea that sustained economic growth is driven by technological progress has long been embedded in the economic growth literature. However, the way in which technological progress can be modeled to generate sustained growth has been quite fuzzy. Neoclassical economists postulate that technological progress is very much like manna from heaven – no deliberate attempt is needed to achieve it in order to promote growth. Dissatisfaction with this so-called exogenous growth had led some economists to model technological progress as a deliberate attempt by the society to produce knowledge or ideas, and this culminated into the so-called endogenous growth theory [for a survey, see Barro & Sala-i-Martin (2004), Grossman & Helpman (1994), Pack (1994), Romer (1994), and Solow (1994)].

Although there are a few available strands of endogenous growth theory, the one that figures prominently is invariably known as the R&D-based growth model, which is evident from the 2018 Nobel Prize in Economic

Sciences, which was jointly awarded to Paul Romer for his pioneering work on this model. Even within this strand, a few varieties exist: one variant hypothesizes that technological progress takes place as a result of a continuous expansion in product variety [Romer (1990) and Grossman & Helpman (1991), Chapter 3] while another variant postulates that technological progress takes places as a result of continuous improvements in product quality [Aghion & Howitt (1992) and Grossman & Helpman (1991), Chapter 4]. While each of these R&D-based models offers a fascinating story of endogenous growth on its own, it remains to see whether technological innovation that has been actively taking place today fits a particular model or more. In other words, it is interesting to explore which of the existing R&D-based growth models matches the current innovation.

Once we start talking about current innovation, one big picture that quickly comes to our mind is information and communication technology (ICT), as evident from the continuous improvement in telephones (beginning with fixed line telephones to mobile phones, and to smartphones) and personal computers (beginning with desktops to laptops and notebooks, and to smartphones). Complementing this ICT is the development and mushrooming of social media with the introduction of Facebook, Twitter, Whatsapp, Telegram, Instagram, etc. Adding to this list of innovations is graphene, a newly extracted carbon-based nanomaterial or, more precisely, an allotrope of carbon atoms that are tightly packed in a hexagonal, honeycomb lattice (Kumar et al., 2013). An alternative way of conceptualizing graphene is by deriving it from graphite which, in turn, is one form of carbon. When a particular arrangement of carbon atoms appears in many layers, they form graphite, and graphene is essentially a single layer of graphite (Geim & Novoselov, 2007).

What is interesting about graphene is that it possesses many superior properties: it is mechanically very stiff, strong, thin, transparent and elastic/flexible; it is electrically very conductive (more conductive than silicon); it is thermally very conductive (more conductive than copper); and it is also completely impermeable to molecules (Novoselov et al., 2012; Kumar et al., 2013; Ren & Cheng, 2014). All of these remarkable properties make graphene an extremely attractive nanomaterial to be studied and ultimately exploited in a host of applications in diverse areas ranging from electronics to photonics, composites, energy storage, medicine and even aerospace (Novoselov et al., 2012; Ferrari et al., 2015).

Of these, electronic applications of graphene have received the overwhelming attention of scientists, industries, and governments due to its electrical property (highly conductive) and mechanical property (highly transparent). Naturally, these properties make graphene a suitable transparent electrode, which is used in certain flexible electronic devices such as touch screens, electronic papers, solar cells, liquid crystal displays (LCDs) and organic light emitting diodes (OLEDs) (Novoselov et al., 2012; Kumar et al., 2013).

Consider touch screens, which are computer display screens that are sensitive to human touch and are often found at automatic teller machines (ATMs), smartphones, and computer game consoles. Like other flexible electronic devices, touch screens require transparent electrode. At present, the material used as transparent electrode is indium tin oxide (ITO). However, ITO is brittle; i.e., it has a low fracture strain (Ahn & Hong, 2014). Since graphene is flexible, it may be a suitable replacement for ITO in the near future. However, the substitution of graphene for ITO is complicated by the fact that touch screens require a transparent electrode that has low sheet resistance and high transmittance where ITO outperforms graphene (Novoselov et al., 2012).

Besides its role as a transparent electrode in flexible electronics, graphene has been argued to play an important role in transistors, which are essentially electronic devices that regulate current or voltage flow. Unlike an electrode, which is "an electric conductor used to make contact with the nonmetallic parts of an electronic circuit" (https://en.wikipedia.org/wiki/), a transistor is "a semiconductor device which acts as either an amplifier for electrical power or a switch for electronic signals" (https://en.wikipedia.org/wiki/). Invented in 1947 and arguably the greatest invention of the 20th century, transistors are currently made of silicon, a chemical element with several remarkable properties too (Woodford, April 27, 2017). As silicon is anticipated to reach its fundamental limit soon, the search for a new, superior material is on its way and graphene appears to be the one. However, the substitution of graphene for silicon is complicated by the fact that graphene has zero band gap (more on this in Section 3).

Both flexible electronics and transistors are electronic devices that serve as intermediate goods in the production of consumer electronics such as ATMs, computer games, televisions, computers, and smartphones. From the perspective of the R&D-based growth models, it is clear that graphene technology that is expected to give rise to flexible electronics and modern transistors fits the increasing product quality model pioneered by Aghion and Howitt (1992). In the physics literature, the anticipated replacement of the existing material(s) by a new one (e.g., graphene) is referred to as disruptive technology (Novoselov et al., 2012); in the economic growth literature, it is referred to as creative destruction. Because the term creative destruction was coined by the late economist Joseph Schumpeter, the model is often referred to as the Schumpeterian growth model, or more broadly, the R&D-based growth model. In the next section, a sketch of this model will be provided with a deliberate reference to graphene technology; for simplicity, the exposition is based on a simplified yet elegant version of the model by Barro & Sala-i-Martin (2004) which, in turn, is based on Aghion and Howitt (1992).

2. The R&D-based Growth Model

Consider an economy consisting of three sectors: final-goods sector (final-output producers), intermediate-goods sector (R&D firms), and household sector (consumers). First, the producers of final output hire labor from the household sector and intermediate goods from the R&D firms to produce final output. Second, the R&D firms invest resources to improve the quality of existing intermediate goods. Finally, consumers maximize their utility subject to the budget constraint. Of these three sectors, the first two deserve some elaboration with a special focus on the intermediate goods.

Consider the intermediate goods. At each point of time, there exists a technology to produce several varieties of intermediate goods indexed by *j*. Letting the total number of these varieties be designated by *N* allows the varieties to be denoted by integers $j = 1, 2, \ldots, N$. Letting *N* be fixed allows us to focus on the ongoing improvements in the quality of a fixed number of intermediate goods. For a given intermediate good *j*, there exists a technology to produce an array of quality of the good. However, only the leading-edge quality is actually produced and sold to the producers of final output. This result follows from the assumption that different qualities of the intermediate good *j* are perfect substitutes; therefore, the invention of a new, higher quality of the good drives out its current, lower quality one. This process is assumed to apply for each of N varieties from time to time; hence, the term creative destruction.

Let us consider the behavior of firms in the first two sectors. Beginning with the final-goods sector, the production function for a representative firm *i* can be expressed as

$$Y_i = AL_i^{1-\alpha} . \sum_{j=1}^{N} (\widetilde{X}_{ij})^{\alpha} \tag{1}$$

where α is a parameter such that $\alpha \in (0,1)$, Y is the quantity of final output, A is a measure of productivity, L is the amount of labor input employed, and $\widetilde{X}$ is the quality-adjusted amount of intermediate goods employed, which is given by $\widetilde{X}_{ij} = q_j^{\kappa} . X_{ij}$, where X is the (raw) amount of intermediate goods employed and q^{κ} is the highest quality level attained so far (of good *j*). Letting the quality ladder of good *j* be indexed by $k = 0, 1, \ldots, \kappa$, then the quality ladder of good *j* can be written as $1, q, q^2, \ldots, q^{\kappa}$. This specification reflects the idea that only the highest quality of good *j* is employed. If we substitute this specification into Eq.(1), we obtain

$$Y_i = AL_i^{1-\alpha} . \sum_{j=1}^{N} (q_j^{\kappa} . X_{ij})^{\alpha} \tag{2}$$

Following the standard producer theory, firm *i* is assumed to maximize its profit,

$$\pi_i = Y_i - w.\, L_i - \sum_{j=1}^{N} P_j X_{ij} \tag{3}$$

with respect to its inputs, L_i and X_{ij}, taken the input prices, P_j and w, as given. (Note that the price of output is normalized to unity.) If we substitute Eq.(2) into Eq.(3), we obtain

$$\pi_i = AL_i^{1-\alpha} . \sum_{j=1}^{N} (q_j^{\kappa} . X_{ij})^{\alpha} - w.\, L_i - \sum_{j=1}^{N} P_j X_{ij} \tag{4}$$

Assuming that labor L_i is fixed, the firm's problem reduces to one of maximizing its profit with respect to X_{ij} only, and this yields the first-order conditions which, in turn, yield the marginal products of X_{ij}. Under competitive assumption, these marginal products are equal to P_j. Equating the two expressions yields the demand function for good *j*:

$$X_j = L.\left[\frac{\alpha A(q_j^\kappa)^\alpha}{P_j}\right]^{\frac{1}{1-\alpha}} \tag{5}$$

Now we turn to the behavior of R&D firms that compete with each other to produce higher quality intermediate goods from time to time. The nature of their competition can be characterized by a two-stage decision making process. First, they decide whether to engage in the R&D investment and if so, how much to invest. Second, upon inventing the new, higher quality intermediate good, they determine its price before it is sold to the final-output firms. Basically, the decision to invest (and how much to invest) depends on the expected flow of profits accrued to the successful, innovating firm, which is the difference between the expected flow of revenues and the expected cost of R&D investment. Since these profits depend partly on the price to be charged, it is sensible to model the firm's behavior backward [which is essentially what Barro & Sala-i-Martin (2004) did].

A key feature of the new intermediate good *j* is that it is costly to invent but non-rivalry in production. Thus, the successful, innovating firm should be given an incentive in the form of the monopoly right to produce and sell the good. However, this monopoly right does not last forever; it ends once a newer, higher quality good is invented. As mentioned earlier, innovation is measured by the multiple *q*; i.e., q^0, q^1, q^2, and so on. Hence, the k^{th} innovator in sector *j* raises the quality from q_{j-1}^κ to q_j^κ and obtains the (instantaneous) flow of profit given by

$$\pi(q_j^\kappa) = (P_j - 1).X_j \tag{6}$$

where the marginal cost of production has been normalized to unity. Since X_j is given by Eq.(5), substituting Eq.(5) into Eq.(6) yields an expression that is free from X_j. Thus, the innovator maximizes this profit with respect to P_j, yielding the optimal price $P_j = 1/\alpha$ which is constant over time and across firms or sectors. Since $\alpha < 1$, it follows that $P_j > 1$ = marginal cost, which is consistent with a characteristic of firms under imperfect competition.

Having determined the price of good *j*, we proceed to the decision to invest. As stated earlier, this decision depends on the expected flow of profits or the present value of profits:

$$V(q_j^\kappa) = \frac{\pi(q_j^\kappa).[1 - e^{-r.T(q_j^\kappa)}]}{r} \tag{7}$$

where π(.) is the profit flow given by Eq.(6), T(.) is the profit duration enjoyed by the innovator, and r is the market rate of return. Inasmuch as the outcome of R&D investment is uncertain, this profit duration is random. As a result, V(.) in Eq.(7) is indeed a random variable to be denoted by its expected value:

$$E[V(q_j^\kappa)] = \frac{\pi(q_j^\kappa)}{r + p(q_j^\kappa)} \tag{8}$$

where p(.) is the probability of a successful innovation which, in turn, depends on the amount of R&D expenditure $Z(q_j^\kappa)$, and the position of the quality ladder q_j^κ:

$$p(q_j^\kappa) = Z(q_j^\kappa).\phi(q_j^\kappa) \tag{9}$$

where the function ϕ(.) specifies the effect of q_j^κ on the probability of success: if future innovations are getting harder and harder, then $\phi'(.) < 0$; otherwise, $\phi'(.) \geq 0$. Basically, the R&D investment is attractive only if the expected return $p(q_j^{\kappa}).E[V(q_{j+1}^{\kappa})]$ is at least as large as the cost $Z(q_j^{\kappa})$. If we entertain the possibility of free entry into the research business (which is a characteristic of monopolistic competition), the decision to invest reduces to one in which the net expected return is zero:

$$p(q_j^{\kappa}).E[V(q_{j+1}^{\kappa})] - Z(q_j^{\kappa}) = 0 \tag{10}$$

As stated earlier, the probability of success p(.) depends partly on the amount of R&D investment Z(.) to be made by the innovating firm. Let us express Z(.) as

$$Z(q_j^{\kappa}) = (q_{j+1}^{\kappa})^{\frac{\alpha}{1-\alpha}}.(\overline{\pi} - r\zeta) \tag{11}$$

where $\overline{\pi} = [\alpha/(1-\alpha)].\alpha^{2/(1-\alpha)}.A^{1/(1-\alpha)}.L.$ Basically, Eq.(11) states that the amount of R&D investment is an increasing function of the quality-ladder position of the intermediate goods: more R&D resources are devoted to the product line with a higher quality ladder than the one with a lower quality ladder.

It remains to specify ϕ(.). Let us specify that

$$\phi(q_j^{\kappa}) = (1/\zeta).(q_{j+1}^{\kappa})^{\frac{\alpha}{1-\alpha}} \tag{12}$$

where ζ is a parameter such that $\zeta > 0$. Basically, Eq.(12) states that as good j climbs up its quality ladder, the subsequent steps are becoming more and more difficult; in other words, future innovations are getting harder and harder.

Although our exposition is confined to the behavior of firms producing final and intermediate goods only, a complete setup of this model requires a set of assumptions on households as well. Collectively, the behavior of these economic agents generates sustained, endogenous growth (owing to the premise that sustained economic growth is generated from purposeful R&D activities). While this feature of the model alone is intrinsically appealing, a compelling feature of the model is its welfare implication, namely, its ability to achieve Pareto optimum. Usually, this outcome is assessed by comparing the performance of the decentralized economy (based on the individual actions of households and firms) to that of the centralized economy (based on the single action of a benevolent social planner), and Pareto optimum is achieved when their performance coincides.

There are two alternative scenarios depending on the presence or absence of the industry leader among the R&D firms. If there is an industry leader, then it can be shown that the rate of return on investment in the decentralized economy is lower than that in the centralized economy. Accordingly, the growth rate of the economy in the former falls short of that in the latter, and Pareto optimum is not achieved. If there is no industry leader (i.e., firms take turn in becoming successful innovators from time to time), then it can be shown that the opposite occurs (i.e., the rate of return on investment and the growth rate in the decentralized economy exceed those of the centralized economy). Since this implies excessive R&D investment by the innovator, Pareto optimum is not achieved as well.

In both cases, the failure of the decentralized economy to achieve Pareto optimum calls for the government intervention in the form of subsidy (in the first case) or tax (in the second case). Basically, there are basically three kinds of subsidy (tax) at the government's disposal: subsidy (tax) to the purchase of intermediate goods, subsidy (tax) to the production of final goods, and subsidy (tax) on the R&D investment. Of the six (three subsidies and three taxes), the second last one (subsidy on the R&D investment) figures prominently in reality. Yet it remains to determine whether this policy option is appropriate for graphene in the first place.

3. An R&D-based Growth Model Interpretation

Now let us confront this model with the "data"; i.e., how well this model fits the development that has been taking place in graphene technology so far (as well as how it deviates from reality). The discovery of graphene and its potential optoelectronic applications have seen burgeoning research interest in other 2D and 3D materials to cater to a variety of new photonic applications (Woodward et al., 2014). While graphene had been theoretically studied as early as 1947 by P. Wallace, the conventional wisdom at that time was that it is infeasible to isolate graphene from graphite due to its unstable atomic structure (Geim & Novoselov, 2007). Hence, it came as a significant breakthrough to the scientific community when in 2004 Andre Geim and Konstantin Novoselov demonstrated a remarkably easy exfoliation of graphene from conventional graphite, a feat which earned them the Nobel Prize in Physics in 2010 (Woodward et al., 2014).

What is interesting about graphene is not its discovery per se but rather the fact that it possesses so many superior properties that can be turned into many useful applications. Many 2D and 3D materials have since been studied for their optical properties, including topological insulators (TIs) and transition metal dichalcogenides (TMDs), and have demonstrated remarkable opto-electronic characteristics including ultrafast recovery times (Bao et al., 2009; Zhang et al., 2009; Song et al., 2010), wide operating spectral bandwidths (Song et al., 2010; Tan et al., 2010), layer dependent absorption properties (Zhang et al., 2015; Li et al., 2014) and even considerably high modulation depths (Ahmad et al., 2016; Howe et al., 2016). As a consequence, it has attracted a huge amount of public and private investment in R&D totaling $2.5 billion (http://www.ceramicindustry.com/articles/95791). In the public domain, the top investors have been the European Union, China, the South Korea, and the United States; in the private domain, the leading companies have been Samsung, IBM, and Nokia (Ferrari et al., 2015; Zurutuza & Marinelli, 2014).

In addition to that, the advances in graphene and other carbon-based nanomaterials such as nanotubes have now spurred the exploration of various other 2D and 3D materials for their potential use in photonics and opto-electronic devices. Among these are TMDs which are a category of materials under the family of 2D materials which is generally atomically thin layered material in nano-meters range (Sun 2016). TMDs exhibit the general formula of MX_2 where M represents the transition metal atom such as Molybdenium (Mo) and Tungsten (W) and X represents the chalcogen atoms such as Sulphide (S) and Selenide (Se) (Bhattacharyya, 2012). These materials show promise as they demonstrate the same characteristics as graphene from graphite, and the weak interlayer bonding of TMDs materials make it easily fabricated using simple mechanical exfoliation, similar to that used to fabricate graphene.

Moreover, TMDs are also good in that they possess the combined advantages of other 2D materials such as graphene and TIs. The blending of the 1T (metallic) and 2H (semiconducting) phases in TMDs make them similar to graphene and TIs in terms of band gap (see the next paragraph) and surface state respectively and thus capable of broadband saturable absorption (Bhattacharyya, 2012). In the field of photonics, the broadband saturable absorption properties of graphene and similar materials is important to ensure its functionality as saturable absorber for the generation of pulsed laser in wide wavelength region.

Although the R&D investment by these public and private entities has been made in diverse areas, it is useful to focus on a specific one, say, transistors. It has been recognized right from the outset that graphene has zero or no band gap, defined as the gap between the space in a material that is fully occupied by electrons (known as the conduction band) and the space in the material that is relatively empty from electrons (known as the valence band). It follows that the presence of this band gap allows electrons in the valence band to travel freely in the conduction band, thereby conducting electricity. Inasmuch as the presence of a band gap is required in the fabrication of transistors, employing graphene as an input in the production of transistors seems to be out of the question (Chahardeh, 2012; Sood et al., 2015).

Nevertheless, there are two ways to overcome this problem: engineer the band gap in graphene or circumvent the need to have a band gap in transistors. Both of these methods have been attempted: in the first case, a group of IBM researchers has found a way to engineer the band gap in graphene; in the second case, a team of scientists from the University of California at Berkeley has found a way to circumvent the zero band gap problem (Johnson, 2010; Yirka, 2013; Ferrari et al., 2015). In both cases, the attempts have been successful during a relatively short period of time, pointing to the relative ease with which the graphene-based transistors can be designed. If we take this outcome at face value (which may need to be qualified in light of possible side effects on unwanted byproducts), we may conclude that climbing up the quality ladder is becoming easier and easier as we accumulate more stock of knowledge, which runs counter to the premise of our model.

One may object to this conclusion by arguing that this outcome could be an isolated incident and that it might not be applicable to other devices. However, if one looks at flexible electronic devices, one could easily be convinced that a similar outcome holds for them as well; i.e., graphene-based touch screens, LCDs, and OLEDs are readily available now (Novoselov et al., 2012; Kumar et al., 2013); as a matter of fact, they have been invented shortly after graphene was isolated.

Despite the relative ease with which the graphene-based devices are invented, their commercialization efforts have been deferred, at least up to this point, due to the high production cost of graphene itself. To date, there exist several methods of synthesizing graphene: mechanical exfoliation, chemical exfoliation, and chemical vapor deposition (Kumar et al., 2013). As usual, there exists a trade-off between low-cost and high-quality graphene: while low-cost graphene is feasible with chemical exfoliation, it comes at the expense of high-quality graphene; by the same token, while high-quality graphene is feasible with chemical vapor deposition, it comes at the expense of low-cost graphene (Ren & Cheng, 2014; Ahn & Hong, 2014). Inasmuch as high-quality graphene is desirable and sometimes crucial, it is not economical at this point to replace the existing, inferior material with graphene. It is not economical, for example, to replace the current ITO-based touch screens with graphene-based ones. Hence, we may conclude that the production cost may dictate the adoption of new technology irrespective of the quality ladder position, a feature which is absent in our model.

4. Conclusion

In this paper, an attempt has been made to give the current graphene mania an economic interpretation via the R&D-based growth model. On the surface, we find that the model provides a fairly good description of the development that has been taking place with regard to graphene exemplified by the introduction of graphene-based devices such as touch screens, electronic papers, solar cells, LCDs, and OLEDs. Upon a closer scrutiny, however, we find that there are some discrepancies between the model and the "data." First, there is some evidence that future innovations are becoming easier and easier, which is equivalent to the saying, "the more we learn, the easier it is to learn further." Second, the model seems to focus on the technology of producing a new intermediate good (i.e., graphene-based devices) to the neglect of the technology of producing a sufficiently low-cost raw material (i.e., graphene itself). It is interesting to see how the conclusions of this model are altered (if any) by the incorporation of these concepts.

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