# Advanced Macro: Growth Theory Lecture 3

Marcel Fafchamps

## 1 Endogenous technological change

### 1.1 Research and Development (Romer 1990)

Endogenous growth theory really begun in earnest when the process of technological change itself was 'endogenized'. Several papers achieved this result pretty much at the same time. We focus on one of them: Romer 1990. The paper (and subsequent book) by Aghion and Howitt uses essentially the same model as Romer, except that they also borrow some ideas from a paper by Grossman and Helpman that we study at the end of this lecture.

After his first attempt at endogenizing growth in 1986, Romer went back at it and wrote an alternative model in which the process of research and development is truly endogenized. The trick is to construct an economy with three stylized sectors. One sector does the research and development for intermediate goods, then sells the patents in a competitive market. The second sector produces the new intermediate goods in a monopolistically competitive manner. The third sector uses intermediate goods to produce a consumer good in a perfectly competitive manner.

This model is solved differently from other models. The reason is that, off the balanced growth path the notation is messy. As we shall see, Romer assumes a standard CES/CRRA utility for the representative consumer. Consequently, along the balanced growth path the interest rate is constant. This is a standard result in this category of models. See the solution to the 2003 homework for the details of the algebra. The way the model is presented is thus to assume a constant interest rate $r$ and to use the static market equilibrium and first order conditions to eliminate as many variables as possible. At the end, we go back to the intertemporal optimality conditions and verify that a balanced growth path indeed exists.

We begin by examining what happens within each period and ignore the time subscript to make things more readable. The production function for final goods is:

$$Y = H_Y^{\alpha} L^{\beta} \int_0^{\infty} x(i)^{1-\alpha-\beta} di$$

where $Y$ is final output (price is numeraire), $H_Y$ is human capital used to produce $Y$, $L$ is labor, and each $x(i)$ is one of a continuum of intermediate goods required for production [think of them as various pieces of capital equipment].

At each point in time only some of the $x(i)$ goods are being produced, i.e., goods indexed from $0 \rightarrow A$ is produced, and those from $A$ until $\infty$ is not produced. $A$ changes as new capital/intermediate goods are invented and put into production.

To see how increasing the range of intermediate goods raises output, imagine that $x(i)$ is constant. With this assumption, the production function simplifies to:

$$\begin{aligned} Y &= H_Y^{\alpha} L^{\beta} x^{1-\alpha-\beta} \int_0^A 1 di \\ &= H_Y^{\alpha} L^{\beta} x^{1-\alpha-\beta} A \end{aligned}$$

This shows that if $A$ can be increased at a constant rate, output can grow at a constant rate as well. Another way to see this is to suppose there are two intermediate goods. Production is then:

$$Y = H_Y^{\alpha} L^{\beta} x_1^{1-\alpha-\beta} + H_Y^{\alpha} L^{\beta} x_2^{1-\alpha-\beta}$$

which shows that every $x(i)$ good multiplies human capital and labor, that is, raises their productivity. This mechanism is the basic engine of growth in this model: by adding new intermediate goods $x(i)$, production can be increased indefinitely (as we will see) without adding to human capital and labor. Note that in this model human capital is just a factor of production which is in constant supply at the level of the economy itself. There is no accumulation of human capital $H_y$ in this model.

The production function for final goods is constant returns to scale, which suggests that producers behave in a perfectly competitive manner. In particular, they behave as price takers with respect to intermediate goods. Let the price of $x(i)$ be denoted $p(i)$. Producers maximize profits:

$$\max_x \int_0^A [H_Y^{\alpha} L^{\beta} x(i)^{1-\alpha-\beta} - p(i)x(i)] di$$

which leads to the following inverse demand for intermediate goods:

$$p(i) = (1 - \alpha - \beta) H_Y^{\alpha} L^{\beta} x(i)^{-\alpha-\beta}$$

We now move to producers of intermediate goods. Before initiating production, they must purchase the patent to produce a particular good $x(i)$, after which they have a monopoly on that good. Since the $x(i)$ goods are substitutes, producers behave in a monopolistically competitive fashion. They need $\eta$ units of final output to produce one unit of $x(i)$ which they then rent to final producers at rental price $p(i)$. Production is financed by borrowing at the market interest rate $r$. Since all producers are identical, we can drop the $i$ subscript. Profit maximization can thus be written:

$$\max_x p(x)x - r\eta x = (1 - \alpha - \beta) H_Y^{\alpha} L^{\beta} x^{1-\alpha-\beta} - r\eta x$$

which leads to the standard markup answer for monopolistic competition models with isoelastic demand:

$$p = \frac{r\eta}{1-\alpha-\beta}$$

This shows that along the balanced growth path $p$ is constant. Profits are $(\alpha+\beta)px$.

Turning to producers of inventions (the research and development sector), their production function is:

$$\dot{A} = \delta H_A A$$

where $H_A$ is the human capital used in R&D. The above production function is reminiscent of Lucas' 1988 production function for human capital: the production of new designs gets easier as the stock of new designs $A$ increases. Free entry in R&D ensures that workers are paid their marginal product, i.e. that:

$$w_H = p_A \delta A$$

where $p_A$ is the price at which inventions (patents) are sold. Romer assumes that patents are auctioned so that the producer of the invention receives all the rent produced by the intention, i.e., all the profit generated by the intermediate good producer. We have:

$$p_A(t) = \int_t^{\infty} e^{-r\tau}\pi(\tau)d\tau$$

where the exponential term is a discount factor and $\pi(t)$ is the profit of an intermediate producer at time $t$.

Finally, we have a consumer with constant relative risk aversion/constant intertemporal elasticity of substitution utility:

$$\int_0^{\infty} \frac{c^{1-\sigma}-1}{1-\sigma}e^{-\rho t}dt$$

The attraction of this kind of utility function is that, in equilibrium, we must have:

$$\frac{\dot{c}}{c} = \frac{r-\rho}{\sigma}$$

The representative consumer collects payments to labor and human capital. There are no net payments to capital since (1) final producers make no profits; (2) intermediate goods producers pay all their profits to purchase inventions; (3) inventions are produced only with human capital. Finally, to close the model, Romer assumes no trade, fixed labor $\bar{L}$ and fixed human capital $\bar{H} = H_Y + H_A$. The rest is solving the model and algebra – see the solution to the 2003 homework.

One feature of the model worth noting is that it can be recast in terms of the standard capital aggregate as follows. Define $K \equiv \eta \int_0^A x(i)di = \eta A x$. Then we have:

$$Y = H_Y^{\alpha}L^{\beta}\int_0^A x^{1-\alpha-\beta}di = H_Y^{\alpha}L^{\beta}Ax^{1-\alpha-\beta} = (AH_Y)^{\alpha}(AL)^{\beta}K^{1-\alpha-\beta}\eta^{\alpha+\beta-1}$$

Provided capital is measured in the usual manner, technological change $A$ enters the production function in the usual manner.

Romer rapidly focuses on the balanced growth path of this economy but he provides no proof of convergence to the balanced path. Matsuyama and Ciccone subsequently showed, using a similar – though not identical – model, that the dynamics of this category of models can be very exotic. The key is that Romer shows that a balanced path exists along which $A$, $Y$, and $K$ grow at constant rates forever. The way he does this is simply to 'guess' that, along this balanced growth path, $x$ should be constant. He also guesses that, although the wage paid to human capital $w_H$ rises over time, the proportion of human capital working in the two sectors remains the same. Then he checks that his guess is correct in the sense that it satisfies all the equations of the system. The key revelation in this checking process is that, if the growth rate of consumption is to be constant, then the interest rate has to be constant too since $\frac{\dot{c}}{c} = \frac{r-\rho}{\sigma}$ at the equilibrium.

Romer has thus shown that endogenous growth is possible. This endogenous growth is based on industrial deepening, that is, the complexification of the production process (more and more different pieces of equipment and intermediate inputs and services needed to produce). It also includes increased diversity of goods (albeit not of final goods) and increasing wages for human capital.

## 1.2 Jones critique

In a paper published in JPE (1995), Chad Jones revisits Romer's model and exposes its knife-edge property. Jones' basic contribution is to point out that if we depart ever so slightly from Romer's key assumption regarding the shape of the R&D production function, we get a very different outcome.

Jones examines the case where:

$$\dot{A} = \delta H_A A^{\phi}$$

The difference with Romer is simply the parameter $\phi$. This parameter captures the strength of externalities in research and development. If $\phi < 1$, the world eventually runs out of discoveries. If $\phi > 1$, growth speeds up over time. If $\phi = 1$, we have the Romer model with balanced growth.

Jones then proceeds to add population growth into the model. The reason for doing so is that if research and development is what fuels growth, a larger population is capable of having more people who are not directly productive and specialize in research and development. Intuitively, an increase in population can compensate for $\phi < 1$. In this case, Jones shows that a balanced growth path $g$ exists with:

$$g = \frac{n}{1-\phi}$$

where $n$ is the population growth rate.

Jones' paper brings out the delicate issue of the relationship between economy size and growth: is it better to be large or to be small? Intuitively, if the benefits from technological change accrue to everyone in the economy, and a larger economy is better able to have a large number of researchers, then it is better to have a large economy with a growing population.

### 1.3 Schumpeterian competition and quality ladder (Grossman & Helpman 1991)

Together with Aghion and Howitt, a series of papers by Grossman and Helpman model endogenous growth as the outcome of a Schumpeterian competition process – that is, competition through innovation. We focus here on their paper that has multiple countries. The paper by Grossman and Helpman also has companions, many of which were written by the authors themselves. [For entertainment value, I encourage you to read the paper by King and Levine in JME 1993: it is a perfect copycat of that of Grossman and Helpman. How do people get away with this kind of stuff, I have no idea.]

As Romer 1990, Grossman and Helpman (hereafter GH) also model research and development. But in their case R&D is the way by which firms compete with each other. The authors' objective is to construct a Schumpeterian model of creative destruction with North-South trade.[1] Their approach differ from that of Romer in three essential respects: (1) innovation is destructive in the sense that new products supersede old products; (2) imitation is possible; (3) two economies interact. The basic idea is that the inventor of a product enjoys monopoly profits as long as the product they invented has not been imitated or superseded by a better product. A key assumption is that the North is better at R&D. In equilibrium, all new research is done in the North. Moreover, competition among firms in the rich country is entirely through R&D. The South has lower costs of production which enable it to imitate existing products but not to innovate.

Formally, there is a fixed set of goods indexed by $\omega$ with $\omega \in [0,1]$. Within this set, goods may be of different quality. Research produces an increment in quality of size $\lambda > 1$ which essentially measures technological advance. [This assumption ensures that the economy can grow at a constant rate since it implies that the percentage jump in quality remains constant, i.e., the absolute size of the jump increases.] The size of this proportional step is the same for all goods and remains the same as quality improves. The initial quality of each good is 1. The quality of good $\omega$ after $j$ innovations, denoted $q_j(\omega)$, is equal to $\lambda^j$.

Consumers have identical preferences of the form:

$$U = \int_0^\infty e^{-\rho t} \log u(t) dt \text{ with}$$

$$\log u(t) = \int_0^1 \log \left[ \sum_j q_j(\omega) x_{jt}(\omega) \right] d\omega$$

[1] Grossman and Helpman have published other versions of their model without North-South trade but I find this one more interesting.

where $x_{jt}(\omega)$ denotes the consumption of quality $j$ of good $\omega$ at time $t$. In each period, consumers allocate their budget $E(t)$ so as to maximize their utility subject to the budget constraint:

$$E(t) = \int_0^1 \left[ \sum_j p_{jt}(\omega) x_{jt}(\omega) \right] d\omega$$

At the optimum, consumers allocate equal expenditure shares to each product type $\omega$ and consumes only the quality that has the best $\frac{p_{jt}(\omega)}{q_j(\omega)}$ ratio. In equilibrium, the best quality always has the best ratio so that we can dispense to extra notation and write $q_t(\omega)$ the quality of the state of the art good $\omega$. The indirect utility function can thus be written:

$$\int_0^\infty e^{-\rho t} \left[ \log E(t) - \int_0^1 \log \frac{p_t(\omega)}{q_t(\omega)} d\omega \right] dt$$

The instantaneous interest rate is denoted $r$. Since consumers are free to land and borrow, intertemporal optimization implies that:

$$\frac{\dot{E}}{E} = r - \rho$$

This is of course a standard result in a log utility model. GH also assumes that investors hold a large portfolio of shares so that idiosyncratic risk is pooled across shares. Consequently, shares are a no risk investment and investors are indifferent between shares and bonds: $r$ is thus the cost of capital.

We can now turn to firms. A firm is essentially an invention and its life-cycle corresponds to that of its invention. In equilibrium only the lowest cost of production firm produces the state-of-the-art product. Consequently, only those firms make a positive (Schumpeterian) profit $\pi > 0$. Once a good is copied, profit drops to 0 for all future periods and the value of the share drops to 0 as well. Let $V(t)$ denote the value of the firm at time $t$. The dividend rate is $\frac{\pi}{V}dt$ while the rate of capital gain/loss is $\frac{\dot{V}}{V}dt$. With probability $fdt$, the invention is superseded and the firm loses al its market to the better product. Arbitrage requires that the expected return on equity be equal to the return on bonds, i.e., that:

$$\frac{\pi}{V} + \frac{\dot{V}}{V} - f = r$$

Our job is now to endogenize all the above variables.

At any point in time, there are three type of producing/profit making firms (all with a different $V, \pi$, etc):

1. Northern firms that are exclusive producers of a state-of-the-art product. These firms face a competitive fringe, the producers of the second to last quality and who will enter if the price charged by the current producer rises above what they could charge for their quality. The proportion (measure) of products which are produced by such firms is denoted $n_{NN.}$

2. Northern firms that are exclusive producers of a state-of-the-art product but face competition from a Southern imitator of the second to last quality. This of course assumes that the Southern imitator can charge a price lower than the Northern competitive fringe. The proportion of such firms/products is denoted $n_{NS}$.

3. Southern imitators that produce a state-of-the-art product. The proportion of such firms is $n_S$. They face potential competition from the Northern producer of the state-of-the-art product.

By construction, at any point in time we have:

$$n_{NN} + n_{NS} + n_S = 1$$

We now turn to technology. Each firm manufactures one unit of output with one unit of labor. The wage rate differs between the North and South, with the assumption that $w_N > w_S$. Firms behave as Bertrand monopolists. Consequently, we have:

1. Case S: The Southern firm captures the whole market by charging the price that its competitive fringe would charge, $w_N$ (or $\varepsilon$ below it). Average spending on the good is thus (since consumption shares are all equal) $\frac{E}{\omega_N}$. Consequently, profit is $\pi_S = (w_N - w_S)\frac{E}{\omega_N}$. All other producers of this particular product sell nothing and make zero profit. All they do is act as a fringe to tie up the price. [Note that if another Southern firm were to imitate as well, both Southern firms would compete in Bertrand fashion and make zero profit. Anticipating this, no Southern firm imitates a product already imitated by another Southern firm.]

2. Case NS: This case occurs when a Northern firm improves the quality of a product previously produced by a Southern firm [which now acts as the fringe]. The Northern firm thus charges price $\lambda w_S$, gets all the market $\frac{E}{\lambda w_S}$, and makes profit $\pi_{NS} = (\lambda w_S - w_N)\frac{E}{\lambda w_S}$.

3. Case NN: This case occurs when a Norther firm improves the quality of a product previously produced by another Northern firm [which now acts as the fringe]. The Northern firm thus charges price $\lambda w_N$, gets all the market $\frac{E}{\lambda w_N}$, and makes profit $\pi_{NN} = (\lambda w_N - w_N)\frac{E}{\lambda w_N}$. [Again, if two firms produce the same product, they will compete in Bertrand fashion and make no profit. This acts to prevent entry.]

Let us now detail the process of imitation and innovation. The probability of success in both imitation and innovation is assumed to follow a Poisson process in which the probability of success does not depend on previous effort. This is obviously a simplifying assumption that is made to simplify the algebra. We also assume that firms in the South cannot innovate, only imitate. This is meant to capture differences in R&D capability. For an imitator, the rate of success is $\mu dt$ while the cost of reverse engineering research is $a_M \mu dt$ where $\mu$

is not a parameter but an endogenous variable measuring imitation effort. For innovation, the probability of success is $\iota dt$ where $\iota$ denotes R&D effort. The cost of innovation $a_{DL}\iota dt$ is assumed lower for the 'leader' (the developer of the last state-of-the-art product of this kind) than for the 'followers' at $a_{DF}$ with $a_{DL} < a_{DF}$. Note, however, that followers have an advantage in that they 'jump' two innovations in one go. It is therefore natural that they have a higher cost of research, since they must typically discover how the last invention works before inventing the new one. In contrast, the leader already knows the state-of-the-art invention. We can now examine different types of invention/imitation sequences:

1. Case NS: A Northern firm innovates after a Southern firm has copied. First, we note that only the leader (the producer of the product before it was imitated by the Southern firm) wishes to undertake R&D, because of its cost advantage. Because of symmetry, we can assume that the level of R&D effort of such firms is $\iota_S$ for all such firms in the North. The expected gain from success is $V_{NS}\iota_S dt$ and the corresponding cost of R&D is $w_N a_{DL}\iota_S dt$. In equilibrium, arbitrage requires that:

$$V_{NS} = a_{DL} w_N \quad \text{whenever } \iota_S > 0$$

2. Case NN: A Northern firm innovates after a Northern firm has innovated. This corresponds to the situation where a Northern firm overtakes another Northern firm. The follower firm would gain $V_{NN}\iota_N dt$ at cost $w_N a_{DF}\iota_N dt$ which implies that:

$$V_{NN} = a_{DF} w_N \text{ whenever } \iota_N > 0$$

   This raises the issue of whether the leader would want to continue innovating to deter other Northern firms from overtaking. GH goes into a long and intricate discussion of hiding research etc. But the bottomline is that it is cheaper for follower to overtake whenever:

$$a_{DF} < a_{DL}(2 - \frac{1}{\lambda})$$

   For instance, if $\lambda = 1.11$, then the above conditions requires that $a_{DF} < 1.1a_{DL}$. In contrast, if the leader wanted to innovate twice, he would have to incur a total cost of $2a_{DL}$. The above therefore implicitly assumes some sort of knowledge externality across firms, otherwise it would cost just as much for the follower to jump two steps as it would to the leader.

3. Case S: A Southern firm imitates. The gain is $V_S\mu dt$ while the cost is $w_S a_M \mu dt$ which leads to the arbitrage condition:

$$V_S = a_M w_S \quad \text{whenever } \mu > 0$$

We can now turn to the equity market. Arbitrage requires that the (expected) value of all firms be equal. Note that the probability that a Northern firm loses its business to a Southern imitator (Northern innovator) is $\mu dt$ ($\iota_N dt$). Similarly for Southern imitators. We also note that $f = \iota_N + \mu$. We thus have:

$$\frac{\pi_{NS}}{V_{NS}} + \frac{\dot{V}_{NS}}{V_{NS}} = r + \mu + \iota_N$$

$$\frac{\pi_{NN}}{V_{NN}} + \frac{\dot{V}_{NN}}{V_{NN}} = r + \mu + \iota_N$$

$$\frac{\pi_S}{V_S} + \frac{\dot{V}_S}{V_S} = r + \iota_S$$

The model is closed by equilibrating the labor markets in the two countries (see paper). This concludes the analysis of the within period equilibrium.

GH then turn to the 'steady state' of this economy and show the existence of a balanced growth rate in which the rate of imitation and innovation are constant over time and consumption expenditures and value of firms grow at a constant rate. Along this balanced path, there is no change in the proportion of products that are produced by Southern imitators, Northern leaders, and Northern followers. (No proof of convergence is provided, at least not in this paper.) These proportion are constant over time. GH consider three types of balanced paths:

1. No innovation: this is a corner type equilibrium in which innovation is too costly and never gets started. The economy does not grow.

2. Only innovation, no imitation: this is the type of equilibrium when imitation is too costly. Aghion and Howitt consider this case in detail (with slightly different notation and assumptions) in their Econometrica paper. Note that this case requires that innovation be done by followers, and thus that the condition for followers to overtake be satisfied (see above).

3. Both innovation and imitation, with or without followers overtaking leaders. This is the case the GH examine in some detail at the end of the paper. They focus mostly on the 'size' of the North and South. In particular they show that the rate of 'technology transfer' (the amount of imitation times the number of Northern firms to be imitated) is an increasing function of the size of both economies. This is because research is more intensive when the North is large while imitation is more intensive when the South is large. They also study subsidies to innovation and observe that policy conclusions depend on the equilibrium configuration. [These comments about 'size' should again be taken with a grain of salt: what determines the size is essentially the extent to which spillovers exist.]

## 1.4 Marrying the two (Aghion and Howitt 1992)

An important contribution to the theory of growth is the 1992 Econometrica paper by Aghion and Howitt. This paper is basically a hybrid of Romer 1990 and Grossman and Helpman 1991.

The basic structure of the model is summarized in Chapter 2 of Aghion and Howitt's textbook on economic growth. Since we have seen this kind of model before, I quickly give the model's highlights. There are $L$ workers each with one unit of labor. Preferences are of the form:

$$U = \int_0^\infty y_\tau e^{-r\tau} d\tau$$

Labor is the single factor of production. Output of the final good or consumption good has the form:

$$y_t = A_t x_t^\alpha$$

where $x_t$ denotes labor devoted to production of the consumption good and where $0 < \alpha < 1$. Over time $A_t$ is raised by new technology. Each time a new technology is invented, $A_t$ goes up by a factor $\gamma > 1$, so that after an innovation $A_{t+1} = \gamma A_t$. Labor is the only input in the production of technology and the total amount of labor devoted to research is denoted $n$. We have:

$$L = x + n$$

As in Grossman and Helpman, innovations are a Poisson process that materialize with probability $\lambda n$. The amount of labor devoted to research depends on the arbitrage condition that the wage rate $w_t$ in the production of the final good equals the return to innovation. Let $v_{t+1}$ denote the expected discounted payoff from an innovation occuring at time $t+1$. The arbitrage condition is:

$$w_t = \lambda v_{t+1}$$

It can be shown that, as in G&H, the incumbent does not do any research in equilibrium. The expected return to an innovation is thus simply the rent $\pi_{t+1}$ accruing to the monopolist of the innovation until the time when an another producer comes up with a new innovation. We have, in expected terms:

$$r v_{t+1} = \pi_{t+1} - \lambda n_{t+1} v_{t+1}$$

from which we obtain:

$$v_{t+1} = \frac{\pi_{t+1}}{r + \lambda n_{t+1}}$$

Let us now turn to the determination of the monopoly rent when the incumbent is the sole producer of the new good. We have:

$$\pi = \max_x p(x)x - wx$$

From the consumer's preferences, we have:

$$p(x) = A\alpha x^{\alpha-1}$$

The first order condition for profit maximization yields:

$$\begin{aligned} x_t &= \left[\frac{\alpha^2}{w_t/A_t}\right]^{\frac{1}{1-\alpha}} \\ &\equiv X\left(\frac{w_t}{A_t}\right) \end{aligned}$$

Hence profit is:

$$\begin{aligned} \pi_t &= (\frac{1}{\alpha}-1)w_t x_t \\ &= (\frac{1}{\alpha}-1)w_t\left[\frac{\alpha^2}{w_t/A_t}\right]^{\frac{1}{1-\alpha}} \\ &\equiv A_t\Pi\left(\frac{w_t}{A_t}\right) \end{aligned}$$

where the function $\Pi(.)$ is defined by the above. Let $\frac{w_t}{A_t} \equiv \omega_t$. At the equilibrium, we end up with a system of two difference equations in $\omega_t$ and $n_t$:

$$\begin{aligned} \omega_t &= \frac{\lambda\gamma\Pi(\omega_{t+1})}{r+\lambda n_{t+1}} \\ L &= n_t + X(\omega_t) \end{aligned}$$

Aghion and Howitt then go on to consider the balanced growth path. As it turns out, this balanced growth path of the economy is a steady state of the above system. By definition of the steady state, $\omega_t = \omega$ and $n_t = n$. They plug these into the difference equations above and obtain:

$$\omega = \frac{\lambda\gamma\Pi(\omega)}{r+\lambda n} \tag{1}$$

$$L = n + X(\omega) \tag{2}$$

If we can find values of $\omega$ and $n$ such that the above two equations are satisfied, then the economy has a steady state of $\omega$ and $n$ – and hence a balanced growth path of the economy. The authors analyze the above system via a graph plotting the loci (1) and (2). The basic idea is that locus (1) is downward sloping while locus (2). Moreover the locus (2) asymptotes the $L$ vertical line. Hence the two loci must intersect and a steady state exists in terms of $\omega$ and $n$. This corresponds to a balanced growth path for the economy as a whole where:

$$y_{t+1} = \gamma y_t$$

Moreover it can be shown that the expected time between two innovations is:

$$E\left[\ln y(\tau+1) - \ln y(\tau)\right] = \lambda n \ln\gamma$$

## 1.5 Lessons on R&D

This concludes our discussion of R&D. The papers presented in this section truly endogenize growth in the sense that they incorporate a deliberate R&D process into their model, although they do so using very different models. In Romer's model, innovation is not destructive; it only adds new products to the economy. This feature makes Romer's model comparable to that of Stokey and Young. In contrast, GH's model is truly Schumpeterian in that no new products are developed but obsolete products are replaced with better products. In Romer's model, inventors are gentle contributors to the common good; in GH invention is an essential ingredient in a harsh survival race among Schumpeterian entrepreneurs.

It is interesting to note that, in both cases, some form of knowledge externality is necessary for innovation and thus growth to continue indefinitely. This is quite explicit in Romer's model because the stock of knowledge enter the production function of innovations directly. In GH's model, externalities are hidden. They occur whenever the cost of overtaking (two jumps) for followers is lower than the cost of making both jumps for the leader. This externality ensures that some innovation continues as firms compete through new products. GH also emphasize another process whereby innovation can continue indefinitely. It is a process where low labor cost imitators play a key role. Although the authors do not discuss this issue in the paper, I suspect that here too externalities are important in the sense that imitation must be sufficiently 'easy' relative to innovation that Southern firms decide to imitate.

The lessons from this first part of the course is that the process of long term growth should be understood as a complex process of accumulation and invention where knowledge externalities play an important role. Human capital in the narrow sense may not be so important after all, except in that it is necessary for R&D. We also suspect that more complicated machinery and larger firms require workers with different skills. In particular, large firms require some form of hierarchical organization in order to function. Command and control require literate administrative staff to write reports (intrafirm circulation of information) and monitor performance (moral hazard). They also require that counts be kept of various tasks, which requires numeracy from the part of many workers, including those on the shop floor. We would therefore expect schooling levels to increase as the size of firms rises. By the same token, as the economy diversifies and complexifies, firm interactions get more complicated, which also requires command, control, and audit functions to be performed. My conjecture is that these features explain why schooling is seen to go hand in hand with the complexification of economies. But this issue still requires empirical investigation.

## 2 Conclusion on Part I

The various theories of growth reviewed so far focus exclusively on the process of growth. Perhaps the best way to describe it is as an effort to understand why sustained growth happens in the world as a whole. In this respect, the various theories we discussed identify several possible engines of long term growth such as: accumulation of physical and human capital and accumulation of technological knowledge. The lesson that comes out of these models is that long-term/permanent growth is not conceivable without accumulation of technological knowledge. This is because physical and human capital are by definition bounded themselves (finite lifespan, depreciation) or have returns that converge to zero over time. Of course, it is possible to write models where this is not true, but that does not mean that they constitute convincing explanations of permanent growth.

Our analysis also brought out the fundamental role that externalities play in the accumulation of knowledge. All the models of permanent growth driven by the accumulation of knowledge have some kind of externalities. Sometimes the externality is stated up front; other times it is buried in the notation (e.g., Grossman and Helpman; Lucas 1988). But the externality is an immediate consequence of the non-rival nature of knowledge: my knowing how to build widgets does not prevent you from knowing how to build them as well. The non-rival nature of knowledge is particularly apparent in academic journals, which can be seen as a deliberate effort to maximize externalities.

The non-rival nature of knowledge is to be distinguished from the possibility of organizing exclusive use. Know-how is a kind of knowledge that, even though it is non-rival, is kept secret so as to ensure exclusive use. Patent laws can be seen as an effort to guarantee exclusive use while at the same time achieving knowledge externalities, since patents can be consulted by the public. In a sense, they are an effort to achieve the kind of outcome that Romer modeled in his 1990 paper. What the papers of both Romer and Grossman and Helpman demonstrate is that the non-rival nature of knowledge makes it imperative that exclusive use be guaranteed so that private investments in R&D be made. This is true in both models even though competition works very differently. If exclusive use is not guaranteed, the only kind of learning that takes place is non deliberate, i.e., of the externalities kind discussed in Stokey and Young. Intuitively, we suspect that growth without deliberate research, i.e., without R&D/application of science to technology, would be quite a bit slower. Consequently, perhaps the strongest and most convincing policy recommendation that comes of the endogenous growth literature is that R&D should be encouraged and that one way of doing so is patent laws.

Other factors such as physical capital and schooling appear secondary as far as world growth is concerned. Of course, new technologies raise the returns to physical capital and, we suspect, to schooling (through effects not really modeled in any of the papers we looked at, I believe). This leads to accumulation. Also, physical capital and newly educated workers may embody a lot of new technology. But they cannot, by themselves, be engines of long-term growth.

In this sense, endogenous growth theory answers fairly well the first question we asked in lecture 1, namely, why are the average standards of living in the world higher today than 250 years ago. It does a much less convincing job of explaining why increased prosperity is so concentrated geographically. We have examined several efforts to apply growth theory concepts to inter-country comparisons. Growth regressions suggest that more prosperous countries save more and send more of their children to school, but we do not know why (in fact the theory predicts that poor countries should invest and study more, not less). Young's model hints that the type of goods countries produce matters because learning is not the same for all goods.

Models with externalities further suggest that interactions between countries are important, that the world should be regarded as a system. In Young, for instance, what happens in the LDC cannot be understood by looking at the LDC in isolation. What happens can only understood if both countries are treated as a system. The same is true for the model by Grossman and Helpman where the parasitic relationship between the DC and LDC country generates unexpected symbiosis whereby imitation by the LDC may serve to trigger innovation in the rich country. Again, what happens in each country cannot be understood in isolation.

In the remaining time we have, we will investigate other important work that help understand the prosperity puzzle. We will first reexamine the role that multiple goods play in the growth process. We will then turn to pecuniary externalities, and finally to geographical effects.