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INNOVATION, COMPETITION, AND WELFARE-ENHANCING MONOPOLY

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ABSTRACT

The basic competitive model with freely available technology is suited for static industries but misleading as applied to major innovative economies for which development of new technologies equals in magnitude around 10% of gross domestic investment. We distinguish free generic technology from proprietary technologies resulting from risky investment with uncertain outcome. The totality of possible outcomes drives the national innovation system and the returns to a particular successful technology cannot be compared to its own direct investment costs. Eureka moments are hardly ever self-enabling and incentives are required to motivate investment attempting to turn them into an innovation. The alternative to a valuable proprietary innovation is not the same innovation freely available but the unchanged generic technology. Growth is concentrated in any country at any time in a few firms in a few industries that are achieving metamorphic technological progress as a result of breakthrough innovations.

So long as the entry and exit of firms using the generic technology sets the price in an industry, one or more price-taking firms can coexist with proprietary technologies yielding more or less substantial quasi-rents to the sunk development costs. Consumer welfare is increased if an innovator creates a proprietary technology such that the market equilibrium price is reduced and output increased. If the technological breakthrough is sufficiently large for the innovator to drive all generic producers out of the industry and increase output as a wealth-maximizing monopolist, consumer welfare is surely increased. After some time, the innovative technology will diffuse into an imitative generic technology. The best innovators develop a stream of innovations so that technological leaders can maintain their status as dominant firm or monopolist for extended periods of time despite lagged diffusion, and consumers benefit from this stream as well. The economics of an innovative nation are different from those of the no-growth stationary state which we teach and fall back on. We propose an ambitious agenda to integrate major research streams treating innovation as an object of economic analysis into our standard models.

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The world's leading economies are characterized by national innovation systems which encourage development of embryonic inventions into successful commercial innovations that reduce costs or improve the qualities of existing products or create entirely new products. Innovation is driven by appropriable opportunity.[1] Appropriability in part depends on government enforcement of intellectual property rights, but may also depend on the nature of the innovation. Opportunity involves creative insight, and frequently arises from scientific discovery that makes possible the previously impossible. Innovation has its critics: it raises standards of living generally, but among producers the gains are concentrated and frequently achieved by the emergence of new firms and industries that may become quite large and displace existing firms and workers. Schumpeter's "creative destruction" evokes the economic churning – rise and fall, entry and exit – caused by rapid "disruptive" technological progress.

The core of our argument is to differentiate between a *generic technology* (and its associated production and cost functions) which is available freely to any potential industry entrant and a *proprietary technology* which is the result of risky investments by a particular firm and not freely available to any entrant. The generic technology corresponds to the traditional concept of technology and may be embodied in physical and/or human capital which is available to entrants at a given market price which may or may not depend on the amount of these resources used by the industry.[2] A proprietary technology may be more or less protected by patents, copyrights, trade secrets, actual secrecy, and/or natural excludability, any or all of which reduce the speed and completeness of imitation by other new or existing firms in the industry.[3] A fundamental condition for firms to invest in creating a proprietary technology is that the expected return from using the technology resulting from the investment instead of the generic technology equals or exceeds the cost of the investment. This cannot happen if the technology is freely available to all entrants since no returns would accrue to the technology. It is a fallacy to conduct a positive or normative analysis on the assumption that the technology is free to all when it would not exist in that case. It is worse to blame the innovator for being inconsistent with our traditional model.

Some legal and institutional arrangements are more conducive to scientific breakthroughs which create technical opportunity, and to converting inventive inspiration (the eureka moment) into actual new commercial technology.[4] For example, intellectual property protections vary greatly as does the possibility of venture financing and public offerings for innovative start-ups; anti-trust law and policy can undo the market outcomes of great innovators, reducing the incentive for any other inventor to try to emulate. Reducing a great idea – an embryonic invention – to practice is an expensive, failure-prone process and the expected returns have to cover the costs, or it will not be pursued. As shown in Table 1, in the major innovative nations, R&D expenditures average upwards from 2 percent of GDP, an amount equal in magnitude to about 10 percent of gross expenditures for creation of new physical capital.[5]

The reality, excitement, hope, and costs of innovation are entirely absent from the received standard model of perfect competition as incorporated in hundreds of textbooks (hereafter RSM). If our long run is simultaneously optimal and hopeless, our science is dismal. The RSM assumes a technology described in the production function – an engineering relationship describing the maximum amount of output that can be produced from any given combination of inputs – that is freely available to all industry participants. The cost function of (efficient) firms is then derived using this production function and input prices. The same conception of production and cost functions is routinely applied in models of monopolistic competition, monopoly, and oligopoly. That is, technology is neither a produced means of production nor an object of (as opposed to given for) economic analysis. This concept is consistent with the long-run of a stationary state and – if exogenous change is permitted – even the Solow-Swan neoclassical growth model, but not with the reality of investment in research and development to produce new technologies.

We propose some amendments to the RSM and monopoly models which make them consistent with the production function as an economic object while preserving important results and pedagogical tractability. The objective is to synthesize key insights of the growing but still separate economics-of-science-and-technology and new-growth-theory literatures and incorporate that synthesis into revised RSM and monopoly models. The specific concepts developed here are mostly familiar to participants in those literatures, but their implications in the RSM and monopoly models may still surprise.

Whether the amendment proposed here is adopted depends on its usefulness in improving the conclusions derived from the RSM and monopoly models.[6] We develop four important new results in the following sections: (a) There can be a competitive equilibrium with proprietary technologies which dominates the RSM equilibrium in the Pareto-welfare sense. (b) A firm profitably innovating a proprietary technology need not face a downward-sloping demand curve for its output. (c) Consumer welfare is increased only if the innovative technology increases the quantity sold and reduces the market price. (d) This surely occurs if the innovating firm drives out all competitors and becomes a monopoly firm operating in the downward-sloping region of its demand curve. In section I we develop the concept of proprietary technology and point to a substantial literature that firms adopting proprietary technologies are the primary means of economic growth. The first two propositions characterizing a competitive equilibrium with an innovating firm are developed in Section II. The model for an innovating firm which emerges as a dominant firm is presented in Section III. Next, we consider the case of an innovating firm which creates a proprietary technology for which the wealth-maximizing strategy drives out all firms using the generic technology, creating a welfare-enhancing monopoly. In Section V, we introduce imitation which limits the incentives for innovation as it diffuses the cost reduction to other firms in the industry. A concluding section summarizes the paper and proposes an agenda of future work to apply the same concepts of technology to other market models.

I. Generic and Proprietary Technologies

Figure 1 from Lamkey (2005) illustrates corn output per acre of farmland used in the United States before and after the arrival of hybrid seed corn around 1935. The RSM applies naturally to conditions to the left of 1935: There is a single, unchanging best way to produce corn and anyone operating a farm has learned it either from parents or farm school. If anyone invented any part of the technology, that has long since entered free common knowledge and use. Zvi Griliches (1957) pioneered the study of economically rational technological change by examining the order of introduction (as well as speed of adoption by farmers) of hybrid seed corn. Darby and Zucker (2006) emphasize that the hybrid seed corn revolution was the result not of a scientific breakthrough which enabled agronomists to develop better hybrid corn species than they knew how to do, but instead was based on appreciation of the commercial importance of a scientific discovery which prevented farmers from saving seed from their crops so that they had to purchase hybrid seed corn each year from its inventor: It was not that cross-breeding to achieve superior crops was previously unknown, it was that double-cross-breeding produced appropriability which motivated seed companies to invest resources in inventing better seed.[7]

No one today can deny the importance of commercial innovation in seed corn in producing ever rising standards of living and social welfare. The enabling invention which started this process – only later augmented by establishment of intellectual property rights as a result of proven benefits – was a method of inventing which could not be readily copied by new entrants. Students of science and technology have long wrestled with differences between dynamic and static welfare illustrated by this example: Once a seed corn is invented, social welfare is maximized (in the static sense) by making the new technology freely available. But if that is done, then there is no expected return to motivate the innovation in the first place and the seed corn is never invented, resulting in dynamic inefficiency. Put differently, welfare analysis is fundamentally flawed if it ignores the cost of and incentives for innovating a technology, and examines technologies only after they have been invented and reduced to practice.[8]

I.A. Self-Enabling versus Embryonic Inventions

Genius is one per cent inspiration and ninety-nine per cent perspiration.

– Thomas A. Edison (spoken circa 1903, published *Harper's Monthly*, 1932)

The arguments over static and dynamic welfare in part reflect two polar opposite views of the knowledge constituting technology. One view is that an invention is created in an "epiphany of insight" or "eureka moment" and once this occurs can be easily understood and used by anyone of reasonable intelligence. Early proponents of this view are Nelson (1959) and Arrow (1962). More recently Romer (1990) argues that technological change is well characterized as "improvement in the instructions for mixing together raw materials," not inherently tied to a human being as human capital, and thus inherently nonrivalrous.[9] If pride of authorship, points toward tenure, or book royalties from publication provide sufficient incentives for all such eureka moments to be codified and published, such *self-enabling* inventions are reasonably described as free gifts of nature which do not require economic motivation for creation or for introduction to the market since any producer has to make the same investment and faces the same cost conditions to enter the market. Our best candidate for an example of a self-enabling invention is how to create hybrid corn seed which does not self-propagate (discussed above); this was an invention of a method of an inventing – a conceptual research tool – which could be understood and applied readily although it took nearly two decades after publication before it resulted in the creation and marketing of any actual seed.

At the other extreme, the same eureka moment is seen as producing only an *embryonic* invention which requires much cooperative investment to reduce it to practice and bring it to market as an innovation.[10] For example, the embryonic invention might be to use a specific receptor on a cell to control or cure a disease. Going from there to a successful innovation might involve developing a prototype molecule that would fit on that receptor, using combinatorial chemistry to create thousands of variants of the prototype, cloning the receptor so that the variant molecules can be screened for which best bind to the receptor, and then identifying the drug-candidate molecules. These candidates then must be tested for activity versus diseased human cells in the Petri dish and activity and safety in animal models. If there are any surviving drug-candidates, one is picked as the best candidate for the very expensive human tests required to prove safety and effectiveness. On the order of 20 percent of the drug candidates that enter clinical trials actually make it through to FDA approval for marketing. DiMasi, Hansen, and Grabowski (2003) estimate that the total R&D cost per new drug approved at 802 million in year

2000 dollars, of which nearly half is accounted for by the cost of capital between outlays and eventual approval. After a drug candidate resulting from an embryonic invention is approved, a major investment in marketing is still required to educate harried physicians on the benefits of the product relative to other treatment strategies.

Our reading of the literatures on the economics and sociology of science and technology is that self-enabling inventions are extremely rare in the history of technological innovation. The great bulk of innovations are embryonic and follow Edison's famous inspiration-perspiration rule requiring much time and resources to turn the embryonic invention into an innovation in product or production. Clearly, most embryonic inventions do not succeed as innovations even after the investment of time and resources. About half of granted patents are allowed to expire by the end of ten years rather than pay relatively small renewal fees (Griliches 1990). We speculate that the vast majority of embryonic inventions are never pursued in the sense of actual investment or resources in an attempt to reduce them to practice, principally due to a lack of incentives, resources, or vision on the part of the inventors.

Governments can do little with respect to vision, but can affect incentives and resources for good or ill. For example, by 1990, 33 and 40 percent of U.S. and Japanese star bioscientists had actively worked with firm scientists to the point of publishing a joint paper, as compared to only 7 percent in Europe (Zucker and Darby 1999). The rank correlation between prevalence of star scientists working in research institutes and star-firm articles was -0.71. (Co-publishing with firm scientists has proven to be a robust indicator of transfer of tacit, naturally excludable technology at the bench level.) We argue that the key factor is the difference in incentives from American and Japanese professors for European star in research institutes whose employees typically get no share of royalties on an invention and cannot participate in founding a new firm while retaining their job at the institute. Besides the apparent differences in the star bioscientists transferring their embryonic technology to industry, we doubt that the lack of industry connection on the part of the remaining 67 and 60 percent of American and Japanese stars represents a lack of embryonic inventions on their part.

The most important policy of most countries with respect to incentives for innovation is the patent law. A good analogy for the role of a patent for an embryonic invention such as a drug candidate is that of the deed for the land on which a skyscraper will be built. Once clear title to the land is secured, the investment in erecting the building makes sense. If instead the building were erected on public land, the building will benefit the public but likely bankrupt the builder. Without the patent on a drug candidate, no rational pharmaceutical company would invest in testing whether it was a safe and effective medicine, since – if they were to succeed – numerous rivals could produce the drug by investing the small cost of proving it chemically equivalent. The market price for the drug would be sufficient to cover only productions costs and the cost of proving chemical equivalence; the original investment in proving it safe and effective and trying many other failed drug candidates would be a loss to the investing firm.

I.B. Introduction of Proprietary Technologies as the Main Engine of Growth

Harberger (1998) has documented that growth is generally concentrated in a few companies in a few industries which are achieving dramatic real cost reductions. Darby and Zucker (2003) have generalized his results to include introduction of new products or qualities of products and distinguish between normal perfective growth and metamorphic growth which transforms existing industries or forms new ones. Theorists following Jovanovic (1982) have developed models in which entry, exit, and reallocation of production among firms with varying productivity drive productivity change at the industry level. Bartelsman and Doms (2000) have recently reviewed the associated empirical literature using business-level microdata that demonstrates that within-industry firm turnover and reallocation shape changes in industry level productivity. Indeed, "these results begin to cast doubt on the appropriateness of an aggregate production function that is based on a representative firm." (p.584) Fogel, Morck, and Yeung (2005) present evidence that countries with more displacement and actual decline of their ten largest firms between 1975 and 1996 experienced faster economic growth in the 1990s. These results are all consistent with the young Schumpeter's belief (1912, recanted by 1942) in the importance of creative destruction by entry of new firms as a driving force for growth.

The industries undergoing metamorphic growth change over time. Famous examples from the past include spinning, weaving, steam engines, steel, glass, electricity, and aircraft. More current examples would be semiconductors, information technology, biotechnology, and nanotechnology. The source of the driving innovations for metamorphic change may be internal or external to the industry, with external innovations using different technological bases the most threatening to existing firms in a transforming industry (Tushman and Anderson 1986).

The good news for the RSM is that most industries at any given time are characterized by little if any technological progress. Unfortunately, ignoring the exceptions – industries with firms achieving metamorphic progress – is fundamentally misleading not only with respect to understanding technological progress but also in understanding industrial organization and the welfare implications of market structures resulting from particular firms generating technological progress via purposive, wealth-maximizing investment in R&D.

II. Competitive Equilibrium with a Proprietary Innovator

If pressed, most economists would agree that it is possible for some entrepreneurs to have technologies superior to that of the typical firm using what we call the generic technology. A rare example of a textbook discussing such infra-marginal firms is Friedman (1976) who attributes these differences as related to superior entrepreneurial capacity. While the existence of firms with superior entrepreneurial capacity means that all firms will not be identical as in the RSM, entry and exit of the generic-technology firms will continue to determine long-run equilibrium. The firm or firms with superior entrepreneurial capacity may earn above-normal returns and differ in size from the standard firms, but they will have no effect on the long-run price and quantity in the industry.[11] Thus, our characterizing some firms in an industry as having proprietary technologies resulting from risky investment might be dismissed as merely relabeling entrepreneurial capacity, but not adding anything of substance to the RSM. We believe our amendment is important, however, because it lays the groundwork in this paper for understanding proprietary technology as a produced means of production not only for a competitive industry as discussed in this section, but also as the firm grows large and faces a downward-sloping demand curve with or without any surviving competitors using the generic or imitative technologies (Sections III-V).

Consider a scientist, engineer, or other potential or current entrepreneur with an embryonic invention which could reduce costs of producing an existing product or introduce an entirely new product or a new quality in an existing product at a cost which will be valued by consumers by more than the cost increase required to produce it using the new technology. The inventor knows that there is some probability that the idea will fail and needs to formulate some assessment of the probability and returns to be earned with different degrees or types of success.

If those expected returns are sufficient and the inventor has sufficient capital to self-finance, he or she will proceed to try to convert the invention to an innovation in the marketplace. Absent self-finance, the inventor will face a cost of capital which depends on the organization, efficiency, expectations, and risk tolerance of the venture capital market. We will restrict our discussion in this section to inventors who can self-finance reduction to practice of a cost-saving innovation for an existing product. The other complications are discussed in the remaining sections or added to the agenda for future research.

The long-run industry equilibrium is illustrated in Figure 2. The long-run equilibrium price P is determined by entry and exit as in the RSM and equal to the minimum average cost of the generic firms. Firm 1 using a proprietary technology produces q_1 where marginal cost MC_1 equals P at an output greater than its own minimum average cost. The cost curves for firm 1 are drawn conventionally excluding the cost of the proprietary technology. The shaded area equal to $q_1(P-AC_1)$ is the quasi-rent returns to the proprietary technology. In any particular case, the net present value of these returns over the life of the technology can be greater or less than the cost of creating the proprietary technology. If expectations are rational, however, on average the NPV of returns to implemented proprietary technologies over all market structures (including those described in future sections) must exceed the expected cost of those technologies by enough to compensate for the failed R&D projects which either produce no new technology or one with higher minimum average cost than the generic technology. Noting that generic firm outputs $q_2 = q_3 = \ldots = q_n = q_{generic}$ are measured relative to correspondingly shifted origins 0_2, 0_3, … , 0_n, the proprietary-technology firm which could be quite large crowds out of the market $q_1/q_{generic}$ firms, but does not affect equilibrium output and price in the market in industries characterized by a horizontal long-run supply curve. A firm with a proprietary technology can shift an upward- or downward-sloping long-run supply curve if it uses more or less of a scarce input than the firms it displaces or otherwise has disproportionate externalities on the other firms in the industry.

Note that the long-run equilibrium price and quantity are undisturbed (with caveats for externalities) if there is more than one proprietary-technology firm so long as some generic firms remain in the market so that their long-run minimum average cost determines the price in the long run. Thus independent inventors or imitators do not affect the quasi-rents to a proprietary technology so long as the combined output of the proprietary-technology firms is less than sufficient to supply the quantity demanded at a price equal to the generic long-run minimum average cost.

As in the RSM, the demand curve D_i faced by each firm i is the industry excess demand curve with its own output subtracted:

(1) $$D_i = D_M - (S_M - S_i),$$

where D_M is the market demand curve, S_M is the market supply curve inclusive of firm i, and S_i is the supply curve of firm i. That is, $S_{M \neq i} = (S_M - S_i)$ is the supply curve of all firms in the market except i, including potential entrants in the long run. The price elasticity E_i of the firm's demand curve D_i at the equilibrium price and output is given by the formula:

(2) $$E_i = (E_M/\sigma_i) - \{[(1-\sigma_i)/\sigma_i]\varepsilon_{M \neq i}\} = [E_M - (1-\sigma_i)\varepsilon_{M \neq i}]/\sigma_i$$

where E_M is the price elasticity of demand for the market, σ_i is the firm's fractional share of the market, and $\varepsilon_{M \neq i}$ is the elasticity of supply of all other firms (including potential entrants for the long-run demand curve). So long as the share of firm i is small, say 0.001, we say that the firm will behave as a price taker because the first term will be so large for any value of E_M which we are likely to encounter. However, suppose that the innovation is metamorphic and the firm has a large share of market output, say 0.5. A wealth-maximizing firm will still behave as a price taker if the elasticity of supply of other firms is sufficiently large, and that quantity $\varepsilon_{M \neq i}$ is infinite in the RSM long run with the usual caveat on the absence of pecuniary or other externalities affecting the market equilibrium.

A myopic short-run-profit maximizer might attempt to reduce output and raise price, to equate short-run marginal revenue and marginal cost, but the resulting entry of new generic firms will reduce future prices and profits for an extended period. This apparent contradiction between profit maximization and wealth maximization reflects the failure to account in myopic marginal revenue for the higher future profits associated with higher levels of current output.

In summary, we have demonstrated in this section that there can be a competitive equilibrium with proprietary technologies. Even if its equilibrium size is large relative to the market, an innovative firm employing proprietary technology will face a horizontal demand curve and act as a price-taker so long as the supply elasticity of other firms is large, as under the conditions corresponding to long-run equilibrium with entry and exit of generic firms. While the proprietary-technology firm is clearly better off given its innovation to be in the market, generic firms earn the same returns in this and other markets and so the displaced firms are no worse off in long run equilibrium. However, a full welfare analysis requires consideration of all the possible outcomes of an investment attempting to convert an embryonic invention into an innovation. Note also that if the innovation can be embodied in a "black-box" machine (or seed) which cannot be copied or reverse engineered, the innovator must compare the costs and returns of entering the product market or the market which produces machinery for the product market. Similarly, if the innovation could be licensed to all market participants with effective protection for intellectual property rights, that route may be the preferred by a wealth-maximizing inventor.

III. The Metamorphic Innovator as a Dominant Firm

Metamorphic innovations – here, a major cost reduction which reduces the average minimum cost of production by a large percentage – can result in a firm which produces a large fraction of the market output. This occurs where the proprietary technology has a much larger output at the minimum average cost and/or a very flat marginal cost curve. We will analyze this case by reinterpreting the traditional dominant firm model.

We first observe that the traditional dominant firm model with a fringe of (generic) competitors does not apply to a constant-cost (horizontal generic-firm-supply-curve) industry because the dominant firm's long-run demand curve given in equation (1) has infinite elasticity and, the firm behaves as a price taker as we saw in the previous section. Thus the discussion in this section is confined to the case of an upward-sloping long-run supply curve for an industry originally made up solely of generic firms.

Figure 3 is the standard dominant firm model, traditionally used to analyze the pricing behavior of a dominant producer firm 1 (say, OPEC) given the supply of a competitive fringe of price-takers. This figure can similarly illustrate the wealth-maximizing output for an innovating firm 1 which replaces much but not all of the production of the generic firms, leaving a competitive fringe. Before firm 1 enters, we would have the RSM long run competitive solution in which a large number of generic firms produce an industry output of Q' which is sold at the market clearing price P'. Now the demand curve faced on entry by firm 1 is simply the negatively sloped excess demand curve D_1 of the generic industry. The demand for the output of firm 1 is thus 0 at the competitive price P' and increases until it corresponds to the entire market demand curve at prices so low that all generic firms have left the market. The wealth-maximizing innovator firm 1 produces Q_1 where its long-run marginal cost MC_1 equals its long-run marginal revenue MR_1, which can occur to the left or right of firm 1's minimum long-run average cost. Given firm 1's output Q_1, the generic firms will supply $Q_{M\neq1}$ for a total market output of Q* corresponding to the market clearing price P* on the market demand curve. Note that consumers unambiguously benefit from the entry of the dominant firm since the new market price P* is lower than the competitive (generic-firms only) equilibrium price P'.

Figure 4 presents the conventional static welfare analysis. Entry of the innovating firm 1 increases consumer surplus by the entire trapezoid bounded by the horizontal lines at P' and P*, the vertical axis and the industry demand curve, but the unshaded portion of this gain to consumers is producer surplus lost by the generic firms. The lighter shaded triangle on the right is the pure gain in consumer surplus. The darker shaded triangle to its left represents resources released from this industry but not counted in the third component of social welfare gain which is the producer surplus of firm 1 measured by the lightly shaded quasi-rents rectangle representing firm 1's output Q_1 times its margin between P* and its average costs (again exclusive of the cost of the innovation). Thus, in this case consumers are unambiguously better off and their gains more than offset the loss of producer surplus by the generic firms. In addition, social welfare is enhanced by resources released from the industry and by the producer surplus of firm 1.

This static welfare analysis is fundamentally incomplete even if the gains are compared to the actual costs of creating the particular proprietary technology utilized by firm 1. It leaves out the uncertainty of the outcome – of which creating a dominant firm is only one possibility and failure is another. Therefore, welfare analysis must properly be applied only to the totality of the national innovation system and not to particular outcomes.

There is a difficulty in the standard dominant firm model generally including its application here to a major innovator. The difficulty arises from taking the supply curve of the generic industry as independent of the output of firm 1 and taking the cost conditions of firm 1 as independent of the output of the generic firms. When the model is applied to an extractive industry in which there are different qualities of deposits and the dominant firm has a vastly larger, high quality deposit, the cost-independence assumptions make perfect sense. But then the fringe of price takers can hardly be characterized as identical generic producers. Upward sloping supply curves for more standard industries are usually justified either by increases in industry output driving up the supply price to all firms of a scarce specialized input or by technical connections among the generic firms as when they use a common resource such as fishing grounds, clean water, or clean air.

If the innovative technology does not require the scarce or common resource then Figures 3 and 4 are properly drawn. Suppose instead that the innovative technology only reduces, for example, the amount of the scarce input used per unit of output. Then a second generic-firm supply curve $S_{M\neq1}$ should be drawn given the equilibrium firm 1 output (and implied use of the scarce input) Q_1 and the cost curves for firm 1 should be drawn given the equilibrium generic firm output $Q_{M\neq1}$. Taking account of these interdependencies both reduces the illustrated gains from the innovation and greatly complicates the diagram. We leave the detailed analysis to our agenda for future research.

IV. The Metamorphic Innovator as Welfare-Enhancing Monopolist

Next, we consider the case of an innovating firm which creates a proprietary technology for which the wealth-maximizing strategy drives out all firms using the generic technology, creating a monopoly despite freedom to enter using the generic technology. Figure 5 essentially replicates Figure 3, except in this case the innovation results in long run marginal costs that intersect the marginal revenue of firm 1 to the right of the output Q" at which all generic firms leave the market.[12] This analysis applies equally to the case in which the generic industry is characterized by a horizontal supply curve and firm 1 becomes a price searcher only at prices below the minimum long-run average cost of the generic firms.[13] The innovating firm's optimal price and output are given by P* and Q*. While consumers do not benefit from the innovation in the case of a constant-cost generic industry when the innovating firm does not drive out all firms, they do if this occurs and output is increased beyond Q". Consumers benefit in increasing-cost generic industries in any case, but benefit more when all generic firms are driven out of the industry by low prices which maximize the innovating firm's wealth.

Note that this is not predatory pricing. The firm is not driving competition out of business to raise prices. The innovating firm's long-run optimal price is so low that no firm using the generic technology can earn a normal return and so all exit. The generic technology is no longer viable.

In the case of new products, there was no prior generic industry because there was no known way to produce the product at a cost consumers would be willing to pay. Since the consumers now have a choice that they value, they are clearly benefited by the new product.

Figure 5 is drawn with a sharp intersection of the generic supply curve $S_{M\neq1}$ with the vertical axis. This implies that the demand curve of the innovating firm D_1 will have a kink at the price P" and output Q" at which the last generic firms exit the industry. As a result of this assumption, the marginal revenue drops at this point. As illustrated in Figure 6, the innovating firm will not choose to increase output beyond Q" or lower price below P" if its marginal cost curve happens to intersect the marginal revenue curve in the vertical portion representing this discontinuity in the price elasticity of demand. This behavior is sometimes referred to as limit pricing. Consumers are no worse off than before the innovation and are in fact better off in the case of an increasing-cost generic industry. The innovating firm 1 would of course be better off if its innovation reduced costs further so that marginal cost intersected marginal revenue to the right of Q'', but there are bound to be some examples in which the special case occurs.

Often, but not necessarily, innovations which result in the market structures discussed in this section are preferable outcomes compared to those analyzed in Sections II and III from the point of view of the innovator. An informal poll of economists, including a number specializing in industrial organization, suggests it is more surprising that consumers are generally better off and always no worse off if a major innovation resulting in a monopoly for the innovating firm occurs. Once again, the difference from the traditional view of monopoly is recognizing that innovative technologies are produced in expectation of returns, and would not exist if the innovation were instead made freely available to any entrant.

V. The Metamorphic Innovator with Imitation

Thus far we have made reference to particular innovation as occurring in the context of a national innovation system which results in numerous attempted innovations, some of which are complete failures, others are an improvement but do not cover even their own sunk costs for R&D much less the risk of failure, and yet others which are very to fabulously successful. Another aspect of success, however, is that it breeds imitation which both limits the duration of the returns and shifts benefits of the innovation to consumers generally over and above any initial benefits from increased consumer surplus.

Patented innovations enter the public domain after a fixed limit of time, or earlier if renewal fees are not paid. Imitation takes many forms: Patents often can be invented around because they are rarely broad enough to cover the insight underlying the eureka idea. For example, the IBM Zurich Research Laboratory scientists J. Georg Bednorz and K. Alexander Müller won the 1987 Nobel Prize in Physics for their 1986 breakthrough discovery that a rare-earth ceramic was superconducting at much higher temperatures than metals. However, others quickly discovered different rare-earth ceramics which were superconducting at even higher temperatures, including the commercially important 77 K (-196°C or -321°F) boiling point of nitrogen, rendering the IBM patent on the original ceramic of no economic value. In other cases, such as recombinant DNA, the techniques used to make the discovery involve so much tacit knowledge that natural excludability limits the ability of other scientists to apply and invent around the discovery.

Here we consider simple imitation (such as at patent expiration) in which previous proprietary technologies are incorporated into the generic technology with a lag of T years. Thus after T years any innovation earns its user only the normal return to the costs to any new entrant. If there is no intervening innovation, the RSM will apply and all the benefits of the innovation are shifted to the consumers (and possibly the owners of scarce specialized inputs whose value is enhanced by the innovation).

Many high-technology industries are characterized by ongoing innovation. Consider here the case of a technology leader (firm 1) and a fringe of imitators using the technology leader's technology of T years prior vintage. We continue to concentrate on cost-saving innovations rather than quality improvements, but expect future research to obtain similar results for the latter types of ongoing innovation. The equilibrium in any given year can be illustrated by Figures 2, 3, 5, or 6, depending on the nature and pace of innovation.

Assume for clarity that the technology leader's R&D program is achieving ongoing cost reductions of R percent per year. Then the minimum long-run average cost of firm 1 ($MLRAC_1$) will equal a fraction of the imitative generic technology firms' $MLRAC_{M\neq 1}$:

(3) $$MLRAC_1 = MLRAC_{M\neq 1}/(1 + r)^T,$$

where $r = R/100$. In practice ongoing innovations tend to also shift out the output $q(MLRAC_i) \equiv q^*_i$ corresponding to the *MLRAC* of firm *i*, so we assume an increasing scale growth rate *S*:

(4) $$q^*_1 = (1 + s)^T\, q^*_{M\neq 1}$$

where $s = S/100$. Further, the demand curve for the industry will shift out horizontally at a growth rate *G* equal to the income elasticity of demand for the product times the growth rate of aggregate income.

V.A. Innovative Leader with Generic Imitators in Competitive Equilibrium

Suppose that the generic and proprietary technologies involve no pecuniary or technical externalities so that the industry has a flat long-run generic supply curve at any instant of time which is shifting downward at *R* percent per annum once the technology leader has been innovating for more than the *T*-year life of a proprietary technology. So long as there are some imitating generic firms, the equilibrium illustrated in Figure 7 will look essentially the same as in Figure 2 – competition with a proprietary technology. Table 2 summarizes some results for this simple model of innovation with competitive imitation.

The first thing to note is that with only a temporary cost advantage over its imitators, the innovative leader still enjoys a cost advantage *k* which is increasing in both the imitation lag *T* and the rate of innovative cost reduction per year *R* (or *r* in decimal terms). Unless the marginal cost curve is vertical at the quantity corresponding to $MLRAC_1$, the innovative leader will produce more than that quantity and have a margin of quasi-rents toward its (excluded) R&D costs that is less than its percentage cost advantage. The leader's output will accordingly exceed that of a representative generic imitator by more than its absolute scale advantage. Once a steady-state growth equilibrium such as described by "Moore's Law" has been achieved, total industry output will grow according to both income and price effects on demand. Price falls at R percent per year governed by the fall in the imitators' $MLRAC_{M \neq 1}$. We cannot generally say whether industry sales will rise or fall relative to GDP or even in absolute terms, since this depends on the price elasticity of demand as well as the rates of fall in costs and income induced increases in demand. It is similarly ambiguous whether the market share of the technology leader will increase, decrease, or stay steady. This uncertainty arises because the growth in the size of the leader depends on the growth rate of the output corresponding to its $MLRAC_1$, while the size of the industry will grow according to both income and price effects on demand.

There can be multiple innovating leaders in this industry with no strategic interaction so long as the imitative generic fringe can still be characterized as determining the industry price with an imitation lag behind the industry leaders. However, even if the industry price is set by lagged imitation by generic imitators, multiple innovating leaders will likely involve strategic interaction on R&D since they are likely to be able to imitate each others innovations much more quickly than non-innovating imitators. Therefore, we will leave further investigation of this market structure to future research.

V.B. Continuing Metamorphic Innovation by a Welfare-Enhancing Monopolist

Analysis of the case of a monopolist engaged in ongoing innovations which are potentially usable by generic technology entrants after a lag *T* is similar to that for imitated price-taking innovators, but inherently messier. We examine only the shifting proprietary and generic technologies in Figure 8, leaving out the demand shifts which are of second order of magnitude for metamorphic progress and would further clutter the analysis. Moving from one year to the next (indicated by a ' sign), we see that the decline in the cost curves due to technology improvement will reduce the wealth-maximizing price and increase the corresponding quantity of output. This provides further benefits to consumers. An interesting feature of this case is that the lagged availability of technological improvements to potential imitative generic entrants progressively lowers what would be the comparable competitive equilibrium price and the price at which some entry will occur. Whether that feature has any impact would depend on the precise shape of the demand curve and position of the cost curves for the proprietary and generic technologies.

Addition of income-induced demand shifts over time as in Section V.A above would work to reinforce the increase in output of the innovating monopolist, but offset the price decrease in whole or part or even – if large enough relative to the pace of innovation – could lead to increasing prices over time. Of course the same would be true for the competitive equilibrium price in a market with an upward-sloping supply curve which shifts down due to technology improvements while output is simultaneously shifting out due to higher income.

VI. Conclusions and Agenda for Future Work

Invention, innovation, and technology have been long compartmentalized in economics, viewed as add-ons for specialists rather than playing any central role in the basic theory. Indeed, the standard model's dismissive theoretical treatment of technology as an engineering statement relating maximum possible output to each combination of inputs makes economists' model of human behavior as motivated by self-interest appear sophisticated by comparison. This treatment is at variance with the fact that advanced economies generally spend 2-3 percent of GDP on research and development – an amount equal in magnitude to around 10% of gross domestic investment. As a leading innovator, American corporate wealth is increasingly concentrated in intellectual property.

Omission of technological change does not simply gloss over descriptive detail; it leads us astray when we make policy recommendations on subjects ranging from intellectual property to anti-trust policy. Almost any economist would argue that R&D which leads to improved technology at a firm in a competitive industry is better for consumers than one that creates conditions such that firm can and does drive all competitors out of business and sets prices as a monopolist. But we have shown in this paper that exactly the opposite conclusion is correct. If the competitive price-taking industrial organization is maintained, the generic firms set the price and all or most of the benefits of the innovation are likely to be captured by the innovator. When the change is sufficiently large and increases scale advantage, the wealth-maximizing innovator sets a price lower than that at which any competitive firm using the generic technology can survive, the gains to consumers are assured and can be quite large. In this case the cost difference between the innovator and the generic firms is so great that the latter are irrelevant to the pricing decision of the innovator.

The totality of possible outcomes drives the national innovation system, and the returns to a particular successful technology cannot be compared to its own direct investment costs. Eureka moments are hardly ever self-enabling and incentives are required for high-risk investment in an attempt to turn inspiration into innovation. The alternative to a valuable proprietary innovation is not the same innovation freely available but the unchanged generic technology.

Growth is concentrated in any country at any time in a few firms in a few industries that are achieving metamorphic technological progress. The best innovators develop a stream of innovations so that technological leaders can maintain their status as dominant firm or monopolist for extended periods of time despite lagged diffusion into the free generic technology, and consumers' benefits grow larger over time as the cost saving grows.

This paper has synthesized ideas developed by many scholars over many decades. An impressive amount of the work was done by affiliates of the productivity program at the National Bureau of Economic Research, led until recently by the sorely missed Zvi Griliches. The first item on the agenda for future work which we are proposing is to make these lessons a central part of the economist's standard model. We believe we have made the case that can and should be done but have no illusions that our efforts here cannot be substantially improved.

We have only essayed incorporating technological change in the form of cost reduction into the competitive, dominant firm, and monopoly models. Much innovation takes the form of creating entirely new products or improving the characteristics of existing products. We see the most obvious next steps to integrate such innovations (as well as cost reductions) into monopolistic competition and oligopoly models.

The ultimate goal is to develop models of innovation for the economy as a whole in which new industries emerge and old ones decline and exit. This model would include an explicit role for advances in basic science and engineering and conditions shaping the transmission of the new, often tacit knowledge to firms. A way station on this path would be explicit treatment of the ongoing replacement by new innovators of firms grown large through prior innovation.

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Footnotes

[1] See, for example, Klevorick, Levin, Nelson, Winter (1995).

[2] The generic technology differs from the traditional concept of technology in that it will generally change over time (as discussed below) in response to the evolution of proprietary technologies.

[3] Natural excludability refers to the property of many discoveries at the scientific frontier which can not be practiced without learning the techniques by working at the bench level with those already adept; this property slows both diffusion to other scientists and imitation by other firms (Zucker, Darby, and Brewer 1998 and Zucker, Darby, and Armstrong 1998). Zucker, Darby, and Torero (2002) present empirical evidence of natural excludability in genetic engineering.

[4] For example, Zucker and Darby (1999) showed that countries which rely on national research institutes have a much lower percentage of their top "star" bioscientists involved in bench-level knowledge flows to firms than countries which rely more heavily on research universities as the locus of basic research. Moser (2005) shows for the second half of the nineteenth century, that invention in countries without patent laws was limited to a small set of industries where there were other means of appropriability, while inventors in countries with patent laws were introducing innovations across a much more diversified set of industries. Lerner and Wulf (2006) report that larger incentives such as stock options and restricted stock for a firm's R&D chief are associated with more patents with higher citation rates and generality.

[5] Neither Canada nor Italy invests as much in R&D as do the G-5 countries.

[6] We believe that similar improvements result in monopolistic competition and oligopoly models, but developing amended versions of those models is beyond the scope of this paper.

[7] Specifically, double-cross breeding produces a first generation crop which is valuable as seed

but does not breed true so that a seed-saving farmer gets a mixture of the inferior constituent strains combined to create the seed corn. Appropriability can be achieved through maintaining secrecy about the constituent strains that work for particular soil and climate conditions or – where available – by intellectual property rights over the use of those true-breeding strains. The advent of effective property rights for seed corn permitted the switch from double-cross to true breeding single-cross seed corn beginning around 1960.

[8] This error is related to the "time inconsistency" problem in macroeconomics in which the central bank wants the public to believe that it is committed to fighting inflation in the future, but in the present increases money supply to lower unemployment since it cannot now affect the public's current expectations.

[9] The Arrow-Nelson-Romer view incorporates two distinct ideas: technological change is simple (cheap) and nonrivalrous. The main argument in the text is concerned with the former. However, the latter is frequently not true either. Cell lines may be cheaply reproducible but the production process involved in producing a drug based on a cell line may be quite complex involving considerable tacit knowledge embodied in particular individuals. Most valuable proprietary technologies are quite complex and embodied in multiple individuals interacting in an organization's task routines each of whom individually could not recreate the technology in a new organization (Nelson and Winter 1982). While the organization is protected from the loss of any particular individual by redundant knowledge, a potential imitator would have to hire a constellation of employees to be able to practice the proprietary technology.

[10] U.S. patent law recognizes the importance of both embryonic inventions and co-operative investment by recognizing priority of invention based on the eureka moment but extending the time in which an inventor has to file for a patent so long as he or she is diligently pursuing its

reduction to practice.

[11] The existence of a firm or firms with superior entrepreneurial capacity could, in fact, affect the long-run price and quantity in the industry if it (they) used sufficiently more or less of a scarce industry factor than the standard firms they displaced that the supply price of that input is changed at the output which would exist if there were only standard firms. Textbook writers can be forgiven for deciding to leave that complication for advanced treatments.

[12] Since all the generic firms have exited in long-run equilibrium, our concerns about the source of the upward slope to the generic supply curve are irrelevant.

[13] In this case the supply curve of the generic industry $S_{M\neq 1}$ is horizontal at P' and marginal revenue of firm 1 equals P' until the market demand curve D_M falls below P'.

Table 1
Research & Development Expenditures and Gross Domestic Investment as Percentage of GDP and Research & Development Expenditures as Percentage of Gross Domestic Investment, 1981-2000

	R&D/GDP	GDI/GDP	R&D/GDI
Canada	1.6	25.0	6.3
France	2.2	24.7	9.0
Germany	2.5	24.0	10.4
Italy	1.1	22.6	4.8
Japan	2.6	32.5	8.1
United Kingdom	2.1	18.6	11.1
United States	2.6	21.3	12.3

Sources: R&D/GDP calculated by authors from data in National Science Board (2004), Appendix Table 4-43, p. A4-89.
GDI/GDP calculated by authors from Investment Share of CGDP [GDP in current prices] data from the Penn World Table (Heston, Summers, and Aten 2002).
R&D/GDI calculated by authors as (R&D/GDP)/(GDI/GDP).

Table 2
Summary of Results for Innovative Leader and Generic Imitators in Competitive Equilibrium

Leader's Cost Advantage (measured at minimum long-run average costs):

$$\frac{MLRAC_{M\neq 1} - MLRAC_1}{MLRAC_{M\neq 1}} = 1 - \frac{1}{(1+r)^T} = k$$

Leader's Margin (exclusive of costs of creating technologies):

$$\frac{P^* - LRAC_1}{P^*} = k \cdot (1 - \frac{\eta_{AC}}{\eta_{MC}})$$

where η_{AC} is the arc elasticity of the leader's average cost with respect to output and η_{MC} is the arc elasticity of the leader's marginal cost with respect to output. Note that $\eta_{AC} \leq \eta_{MC}/2$ so long as the marginal cost curve is concave from above; thus the leader's margin is expected exceed half of its cost advantage.

Leader's Scale Advantage (measured at minimum long-run average costs):

$$\frac{q(MLRAC_1)}{q(MLRAC_{M\neq 1})} = (1+s)^T = \beta$$

Leader's Output:

$$\frac{q_1}{q(MLRAC_{M\neq 1})} = \frac{q_1}{q_{M\neq 1}} = \beta \cdot [1 + (\frac{1}{\eta_{MC}} \cdot \frac{k}{1-k})$$

The leader's output exceeds each generic-imitator firm's output not only in proportion to the leader's scale advantage but also by a factor which is increasing in the cost advantage and decreasing in the elasticity of the leader's marginal cost with respect to output.

Growth Rates of the Total Industry (in percent per annum):

$$\frac{100}{Q^*} \cdot \frac{dQ^*}{dt} = G - E_M \cdot R \qquad \text{or} \qquad \frac{100}{P^*Q^*} \cdot \frac{d(P^*Q^*)}{dt} = G - (E_M - 1) \cdot R$$

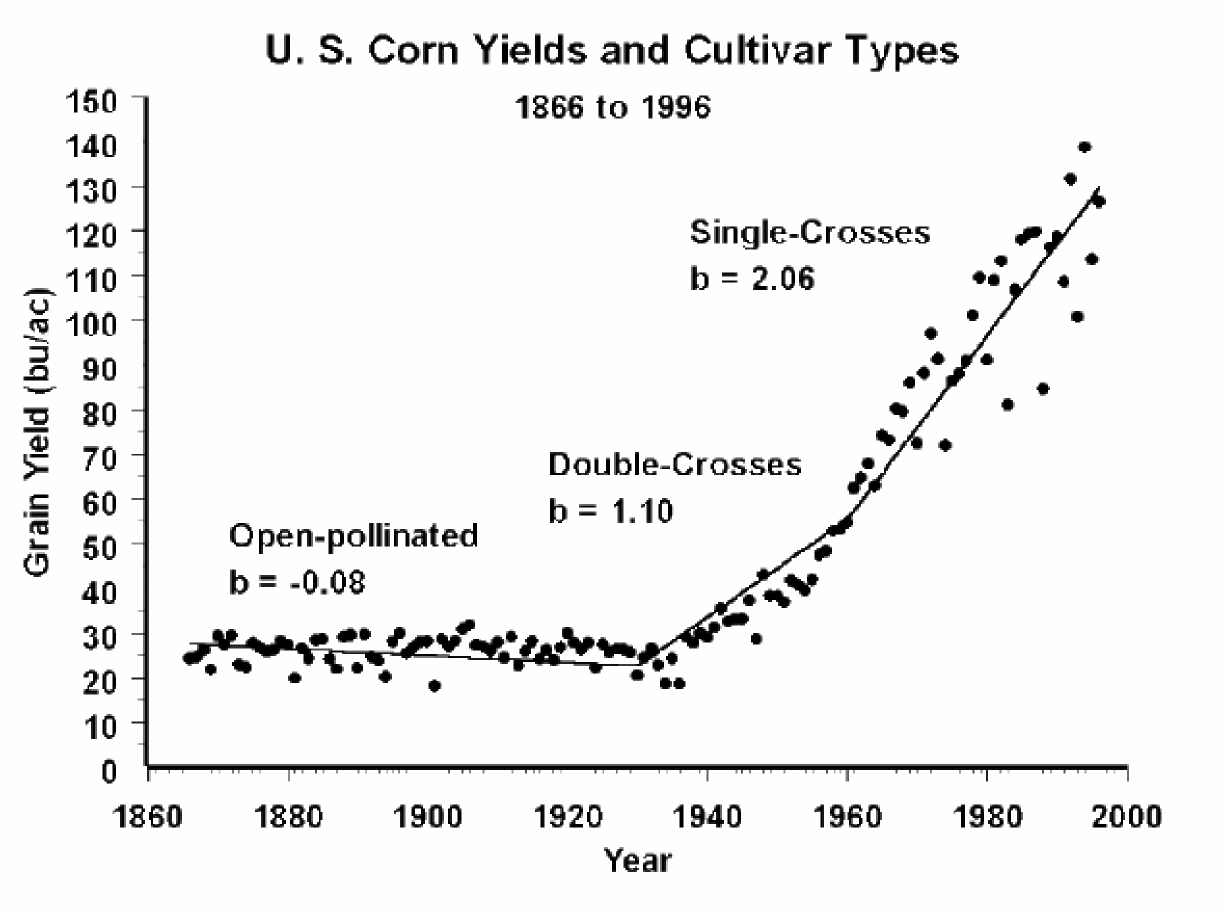
where E_M is the (negatively signed) price elasticity of market demand. Entry or exit ensure that total output of all firms grows according to the income-induced shift in demand G plus the movement along the market demand curve due to the market price fall at the rate R. The growth rate of industry revenue accounts for the rate of price decrease.

Growth Rate of Leader's Market Share (in percent per annum):

$$\frac{100}{\sigma_1} \cdot \frac{d\sigma_1}{dt} = S - (G - E_M \cdot R)$$

The leader's output (and each generic-imitator firm's output) grows at the growth rate S of the leader's scale advantage; its share grows depending on whether this is greater or less than the growth of industry output.

Figure 1. Stationary and Innovative Growth Equilibria



Source: Lamkey (2005).

Figure 2. Long-run competitive equilibrium for industry with firm with proprietary technology

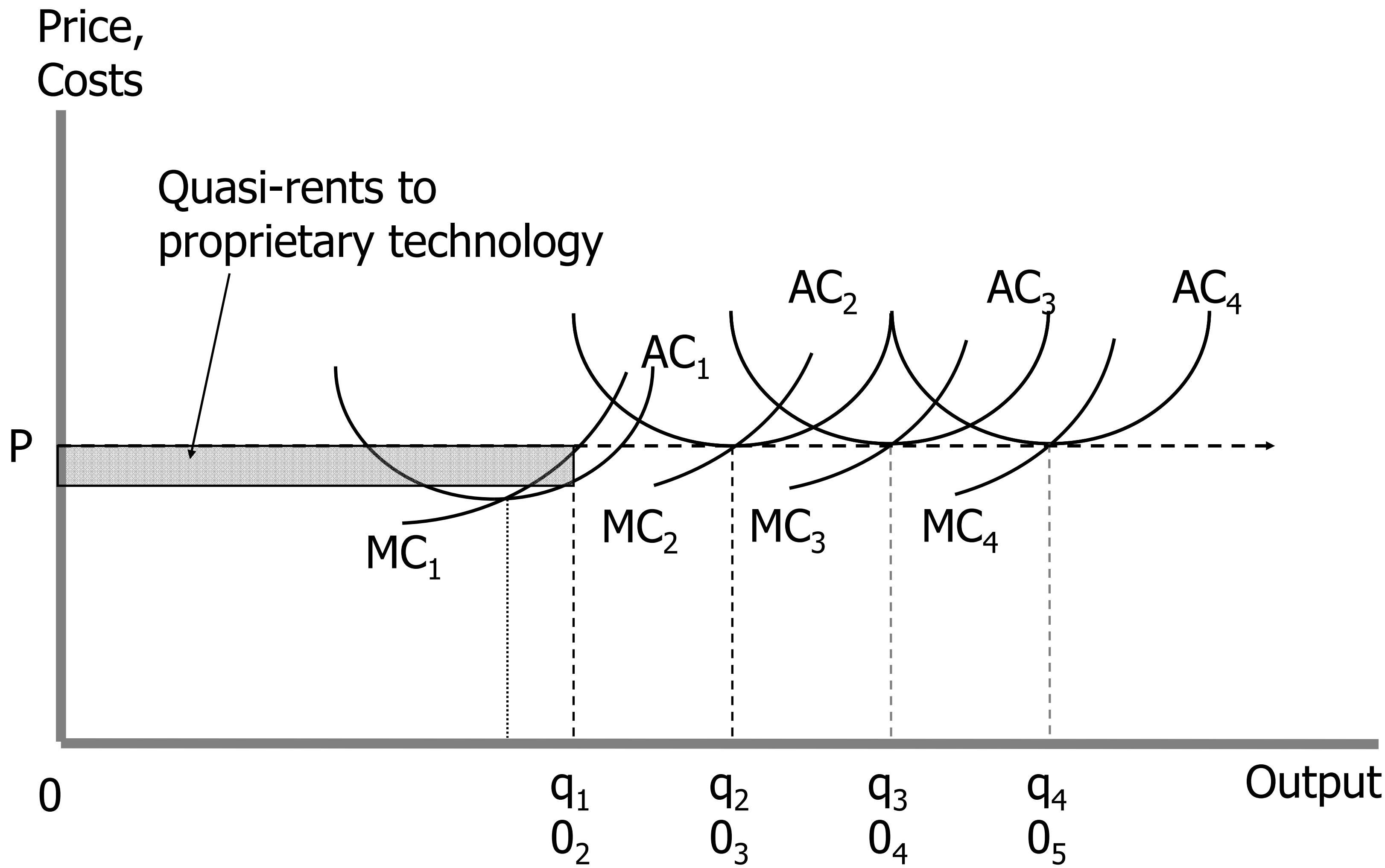


Figure 3. Long-run wealth-maximizing strategy for a dominant firm with proprietary technology

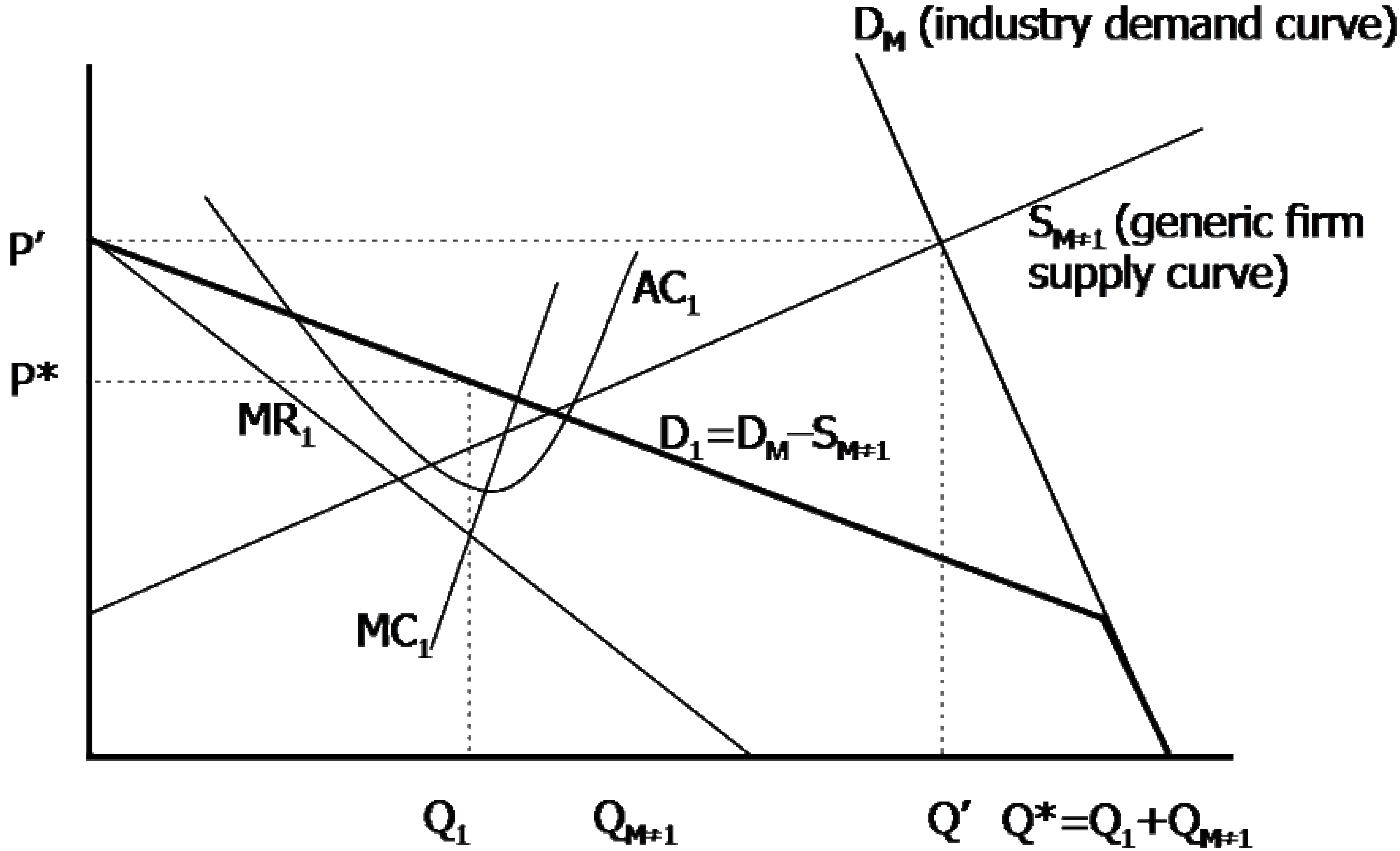


Figure 4. Static welfare analysis for entry into a competitive industry by a dominant firm with proprietary technology

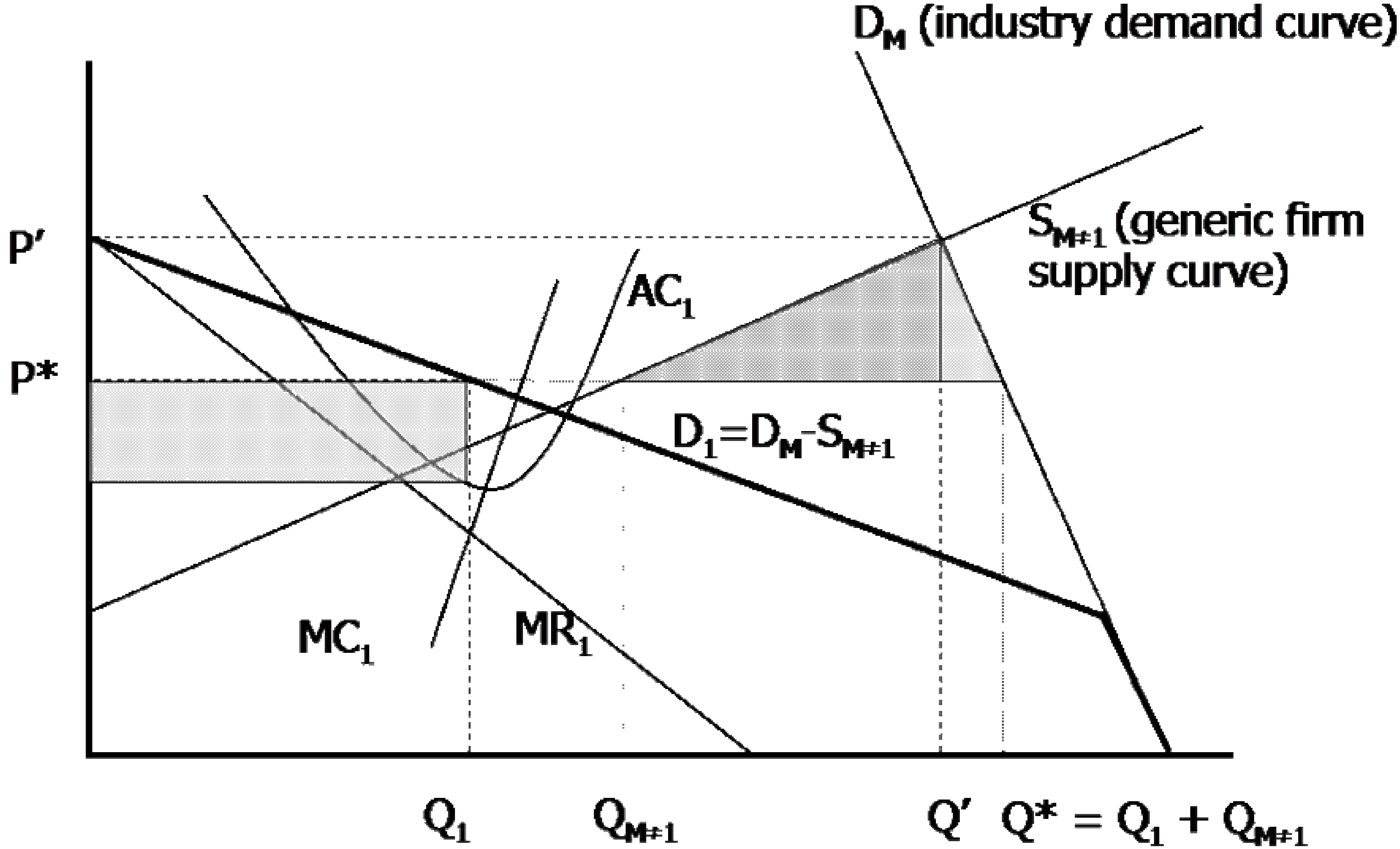


Figure 5. Metamorphic innovation creates monopoly firm with proprietary technology despite free entry of generic firms

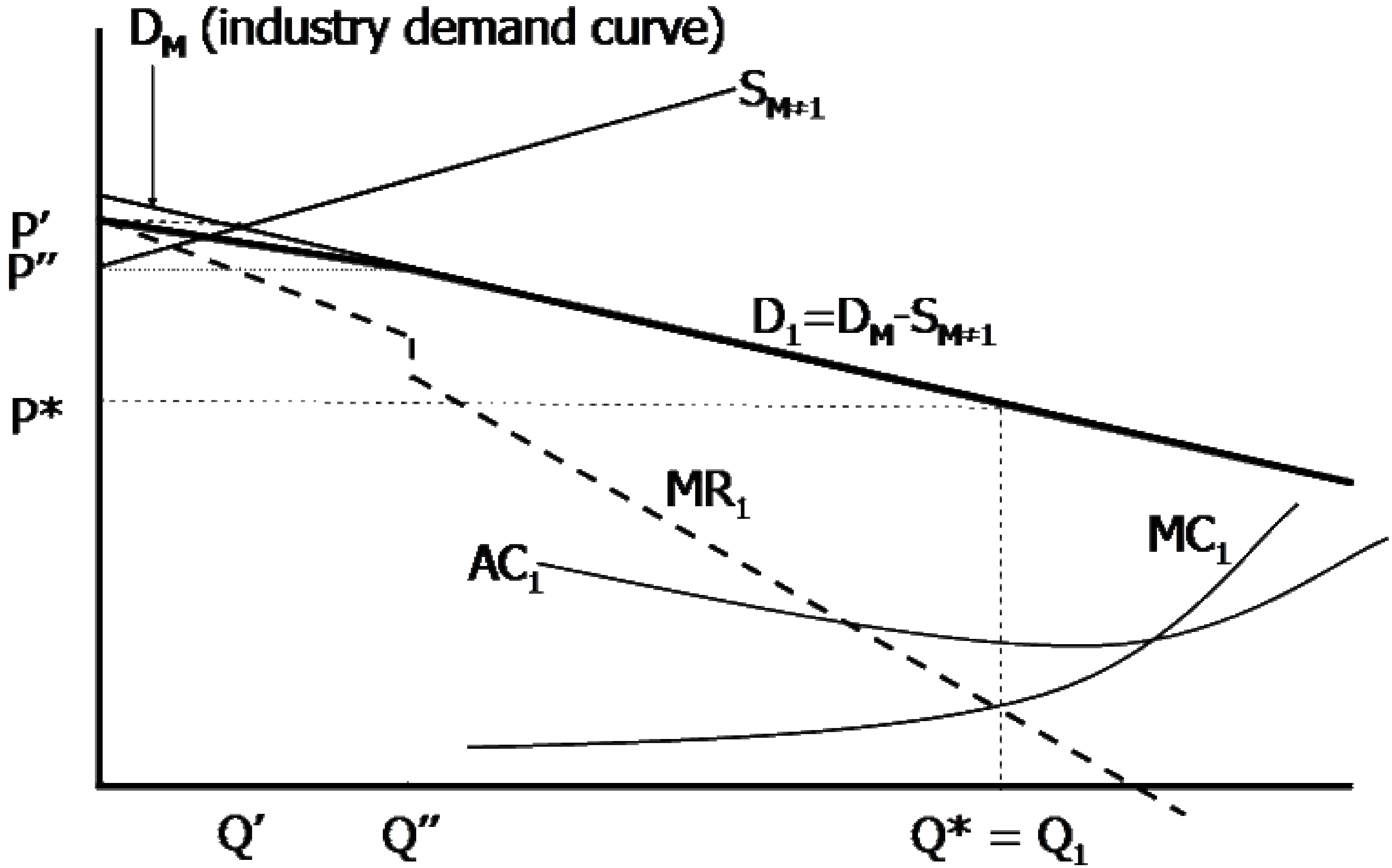


Figure 6. Metamorphic innovation creates monopoly firm with proprietary technology and limit pricing

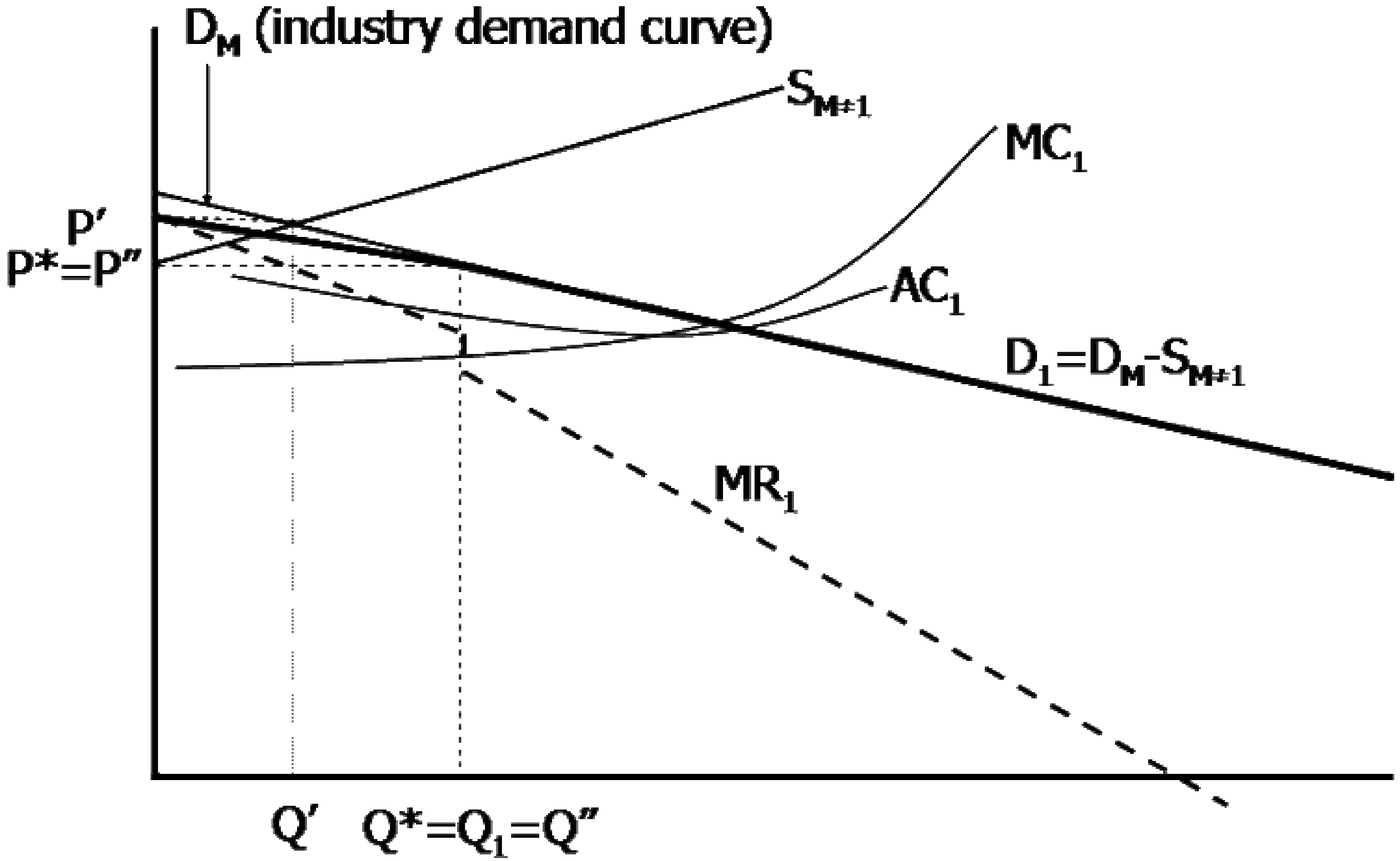


Figure 7. An Innovative Leader with Generic Imitators in Competitive Equilibrium

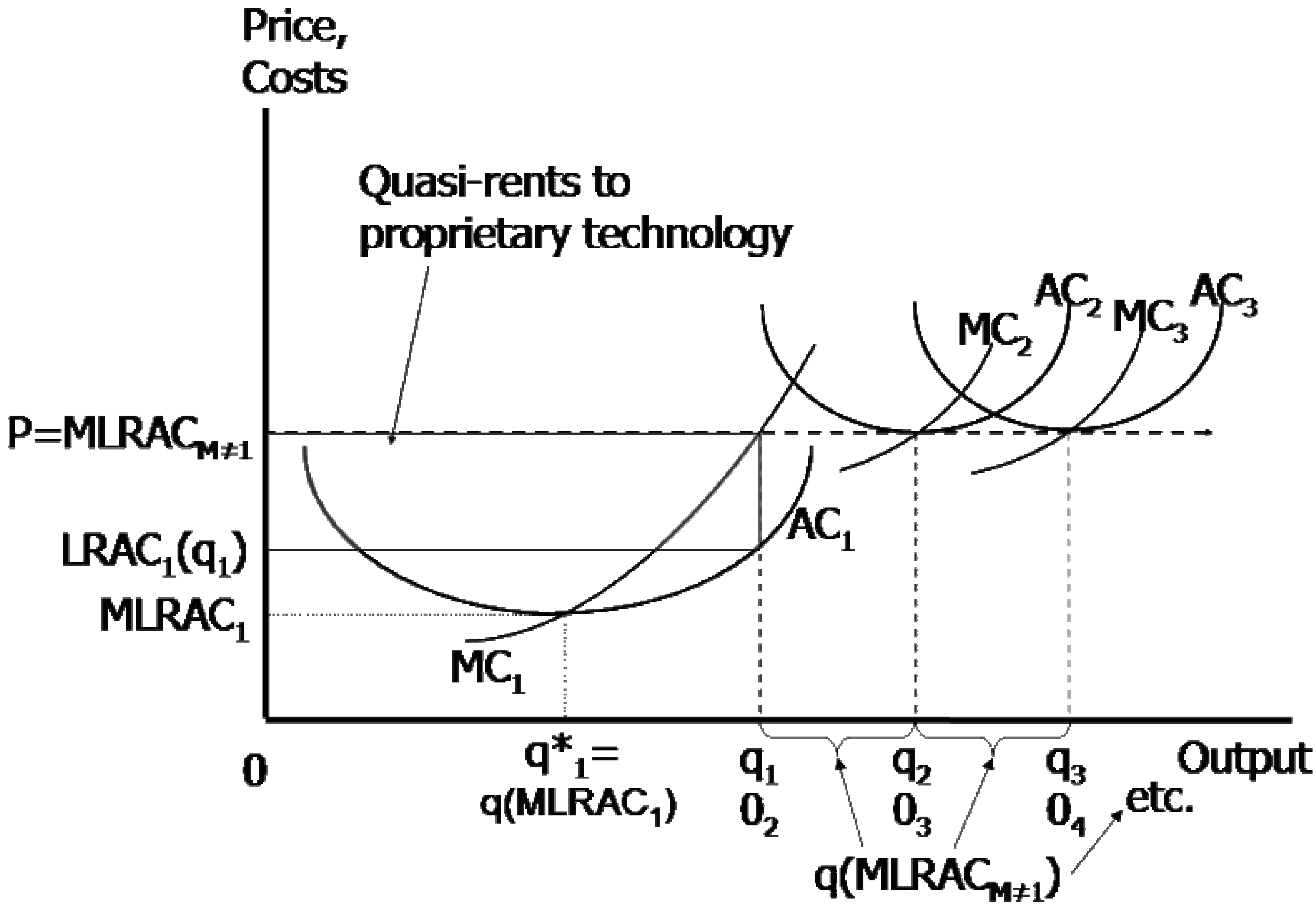


Figure 8. Monopolist with Ongoing Metamorphic Innovation