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Technological Gap and Heterogeneous Oligopoly

Weihong HUANG*, Yang ZHANG†

Abstract

This paper explores the effect of technological gap on output, profits, market concentration, and social welfare in quantity setting oligopoly with firms of unequal sizes, holding different conjectures, operating with non-identical costs, and producing homogenous products. Assuming firms with relatively advanced technology adopt sophisticated Cournot strategy while the remaining with backward technology behave as price takers, we find that an increase in technological gap between two types of firms may paradoxically lead to higher profits for not only the advanced but also the backward. Moreover, wider technological distance could lead to lower market concentration and be welfare enhancing.

Keywords: Technological gap, heterogeneous oligopoly, market concentration, social welfare
JEL Code: L13, D21

1 Introduction

Casual empiricism suggests that firms within industries often deliberately adopt different technologies even when firms have identical opportunity sets. In the brewery industry we see breweries with large capital-intensive plants producing for both home and broad together with labor-intensive mini-breweries selling only domestically and for small segments of the local market. Steel is manufactured in large integrated steel mills as well as mini-mills that convert scrap. Paper and paper products are manufactured by companies which, variously, make or buy their supplies of wood pulp. According to empirical observation, new technologies are adopted by firms with delay and they are diffused over time. One prominent example is the computer numerically controlled machine tools (CNC) which enhances significantly productivity compared

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with conventional general-purpose machines. CNC became commercially available since the mid-1970s, however, as indicated by studies of the U.S. machining-intensive industries, in 1987 less than 50% of firms used CNC tools and the percentage exceeded 80% in 2002¹.

Notwithstanding the ample example, few studies in the literature investigate the reason why firms voluntarily opt for inferior technology and hence delaying the catching-up. In this paper, we provide a model to demonstrate that wider technology gap could not only be profit-enhancing but also desirable when market competition and social welfare are concerned.

In the literature on the choice of technology, the adoption of convex technologies of different efficiencies have been explored by Eaton and Eswaran (1997), Hansen and Nielsen (2010) and, more recently, by Milliou and Petrakis (2011) and Pérez and Ponce (2015). The goal of these articles is to understand how firms may diversify their technologies for strategic reasons (Hansen and Nielsen, 2010), the timing in relation with production market competition (Milliou and Petrakis, 2011) and the adoption with involving disruption costs and learning by doing (Pérez and Ponce, 2015). In public economics literature technological gap and the consequent asymmetry in cost efficiency have been studied concerning optimal taxation (Dung, 1993), the welfare effects of subsidies in particular (Hamilton and Sandin, 1997) and trade policy instruments in general (Collie, 2006; Lahiri and Ono, 1997). Their analysis, however, mainly focus on homogenous firms.

Our work is also related to a list of articles on the effects of behavioral heterogeneity in oligopolistic markets. The coexistence and interaction of behaviorally heterogeneous agents have been studied between profit and relative profit maximizing firms (Riechmann, 2006), between simple and naïve behavior and more sophisticated strategies (Huang, 2003) and between optimizers and imitators (Schipper, 2009). More recently, quantity competition has been analyzed in oligopoly consisting of profit maximizers and firms following an alternative criterion (Chirco et al, 2013) as well as of profit-maximizing firms and socially concerned firms (Kopel et al, 2014).

Heterogenous oligopoly, however, especially the case where some firms behave strategically while others taking price parametrically, has been mostly studied under the assumption of identical cost structure industry wide. The issue of technological gaps, deliberately chosen or due to different qualities of inputs, has largely remained under-researched. Indeed, heterogeneous oligopoly is more relevant for the investigation of technological gaps where agents across strategy groups are potentially subject to different production technologies in terms of efficiency. This is

¹See Bartel et al. 2007.

a key distinctive feature of our work.

Accordingly, this paper adopts the framework of prior literature and makes two contributions. First, the main motivation we offer for the exercise is methodological: to derive, for the model adopted, certain results of general interest and applicability in the industrial organization literature. Considering an oligopoly model allowing for behavioral asymmetries, we assume that advanced Cournot firms equate their marginal revenue to marginal cost and simultaneously the remaining players equate their marginal cost to market price. Price-taking firms have been studied in many oligopoly literature such as the competitive fringe model in Stackelberg game (Asada and Semmer, 2004) and the cartel-fringe game (Bencheikroun and Withagen, 2012). Increasingly the Walrasian behavior building on its central hypothesis that agents take prices parametrically has been studied in the evolutionary game theory literature since the seminal work of Vega-Redondo (1997). Firms adopting the price-taking strategy are found to outperform dynamic optimizer in a heterogeneous duopoly (Huang, 2011). The second contribution is to shed new lights on the incentive/disincentive for technological catching up. Particularly, we evaluate the effect of technological gap between the two strategic groups on output, profits, industry concentration and social welfare.

Our results reveal that widening technological gap could actually lead to higher profits for both the leader and laggard firms and that inferior technology is entirely possible to be adopted voluntarily by the backward firms. Also, backward firms deviating from technological leader in the industry could result in lower degree of market concentration and can be welfare improving. Deliberate distance from technological leader in the industry and the resultant preference over inferior technology turn out to be, in asymmetric oligopoly, a distinct possibility. Our results can explain why different technologies coexist in a homogenous goods market and shed some lights on the rationale of relatively inferior technology deliberately adopted by oligopolistic producers. Our model can provide some theoretical ground on the postponement in the diffusion of and the strategic timing of the adoption of new technologies.

The remainder of the paper is organized as follows. Section 2 introduces the model and elaborates the equilibrium analysis. Section 3 presents a numerical example which provides us with simple and empirically very plausible condition under which technological catching-up can be demotivating. Section 4 concludes.

2 Model and Implications

Consider N firms each producing q^i , $i = 1, 2, \dots, N$, of a homogeneous product with an inverse demand function $p = D(q^d)$ with $D' < 0$. For every $q^d = \sum_{i=1}^N q^i$ supplied to the market, D specifies the market-clearing price.

Firms are grouped into two categories: m firms are “Advanced” and $(N - m)$ firms are “Backward”. Backward firms adopt less efficient technology and have no other market information (such as the market demand D , the composition of the industry, and the outputs of the rivals) except the price p . Therefore, they have to behave as price-takers. On the contrary, the remaining firms are advanced in the sense that they have more efficient technology and more market information so that they can adopt more advanced strategy through best-responding to the outputs of the backward.

The assumption of price-taking behavior of the backward firms can be justified in the following ways. When cost differentiation is allowed in heterogeneous oligopoly², it is common to assume the price-takers to have cost disadvantage over the more sophisticated firms (Asada and Semmer, 2004), potentially because the latter enjoy better management or patented technology, or the benefit of economies of scale. Moreover, one may imagine that price-taking strategy being simpler than the Cournot one requires smaller cognitive cost to implement. For firms with inferior technology, the cognitive cost of finding the optimal strategy is not worth paying. In addition, it is possible that backward firms enter into an agreement to behave as price-takers. Such a collusive behavior is hard to detect and it may go unnoticed by antitrust authorities. Therefore, the equilibrium is determined jointly by each Cournot player’s quantity best response curve and the supply curve of each price-taking firm.³

Assume that firms within their respective category adopt an identical convex technology. For the simplicity of comparison and discussion, we shall let $c_j(q) = C(q)$, with $C'' > 0$ for $j \in$ Advanced, and $c_j(q) = (1 + \epsilon)C(q)$, for $j \in$ Backward, where $\epsilon \geq 0$ is the inefficiency parameter

²Without loss of generality, cost function here reflects overall cost structure of firms including the search cost for technology and the cognitive cost to implement the chosen strategy. Backward firms operate on less efficient production technology and as a result face a higher cost function (even after taking into account the cognitive cost for adopting the simpler price-taking strategy).

³The setting is different from the standard competitive fringe model characterized by strategic Cournot firms taking the supply functions of the fringe firms as given in deciding their own quantities. This essentially pertains to a Stackelberg model where the Cournot firms act as leaders while the fringe firms as followers. Our model instead builds on earlier literature on conjecture variation models, see for example Dung, 1993, Kamien and Schwartz 1983.

gauging the technological gap between the two groups.

Let x be the individual output of the backward firm and y be the output of the advanced firms. Then x is determined by $p = (1 + \epsilon)C'(x)$, that is⁴,

$$D((N - m)x + my) = (1 + \epsilon)C'(x) \quad (1)$$

while y is determined by $p + y(dp/dy) = C'(y)$, or, equivalently,

$$D(my + (N - m)x) + D'y = C'(y). \quad (2)$$

Eqs. (1) and (2) jointly determine a unique equilibrium $(\bar{x}(\epsilon), \bar{y}(\epsilon))$ with $\bar{x}(\epsilon) > 0$ and $\bar{y}(\epsilon) > 0$, so that

$$\begin{cases} D(\bar{q}(\epsilon)) = (1 + \epsilon)C'(\bar{x}(\epsilon)), \\ D(\bar{q}(\epsilon)) = C'(\bar{y}(\epsilon)) - \bar{y}D'(\bar{q}(\epsilon)), \end{cases}$$

where $\bar{q}(\epsilon) = (N - m)\bar{x}(\epsilon) + m\bar{y}(\epsilon)$.

Let $\bar{\pi}^x$ and $\bar{\pi}^y$ be the equilibrium profit for each firm in the respective category. Then we have

$$\begin{cases} \bar{\pi}^x(x, y) = \bar{x}D(\bar{q}) - (1 + \epsilon)C(\bar{x}), \\ \bar{\pi}^y(x, y) = \bar{y}D(\bar{q}) - C(\bar{y}). \end{cases}$$

It is well-known that, the convexity of C would imply $(\bar{x} - \bar{y})C'(\bar{x}) - (C(\bar{x}) - C(\bar{y})) > 0$ for $\bar{x} \neq \bar{y}$, which in turn suggests $\bar{\pi}^x(x, y) > \bar{\pi}^y(x, y)$ for $\epsilon = 0$ for the sake of $C'(\bar{x}) = D(\bar{q})$. Consequently, it follows from the continuities of D and C that there must exist an upper limit to ϵ , denoted as ϵ^* within which the backward makes higher profit than the advanced. In particular, we have the following:

Proposition 1 *When $C' > 0$ and $C'' > 0$,*

- i) there exists a unique $\epsilon^\#$ such that for all $\epsilon \in [0, \epsilon^\#)$, $\bar{x} > \bar{y}$;*
- ii) there exists a unique $\epsilon^* < \epsilon^\#$ such that for all $\epsilon \in [0, \epsilon^*)$, $\bar{\pi}^x(x, y) > \bar{\pi}^y(x, y)$.*

Here $\epsilon^\#$ is derived from the identity $\bar{x}(\epsilon^\#) = \bar{y}(\epsilon^\#)$ and ϵ^* from $\bar{\pi}^x(x(\epsilon^*), y(\epsilon^*)) = \bar{\pi}^y(x(\epsilon^*), y(\epsilon^*))$. Alternatively, $\epsilon^\# = -\bar{y}(\epsilon^\#)D' / C'(\bar{y}(\epsilon^\#))$, and

$$\epsilon^* = -1 + C(\bar{y}(\epsilon^*)) / [C(\bar{x}(\epsilon^*)) - C'(\bar{x}(\epsilon^*))(\bar{x}(\epsilon^*) - \bar{y}(\epsilon^*))] > 0.$$

⁴Note that the backwards are assumed to be deficient in market information so that their only strategy is simple Cobweb strategy, that is, acting as *price-takers* with naive price expectations: $\hat{p}_{j,t} = p_{t-1}$ and planning its production based on $p_{t-1} = MC_t^j$, for $j = m + 1, m + 2, \dots, N$. We thank the autonomous referee for pointing out this important clarification.

For the clarity of presentation, proofs for all propositions and theorems appear in Appendices. For profit comparison between Cournot and the price taking firms with equal cost function, it is obvious that the competitive price takers do better than Cournot counterparts for the reason that they don't have to restrict their output and bear the cost of achieving high price. Given continuity, there is some scope to allow for cost differences without losing this property. That is to say, backwards firms indeed commit to a higher output than the Cournot equilibrium output and in a sense, taking the price as given is like having a first mover advantage. What interests us next is, when facing a choice of technologies of different efficiency (a choice of various ϵ), whether the backward firms will always prefer a more advanced technology (smaller ϵ).

2.1 Impact of technology gap on firms

To have determinate conclusion in the comparative statics, the following conventional assumptions are imposed.

Definition 2 *By conventional assumptions, we mean i) $D' < 0$, ii) $C' > 0, C'' > 0$, and iii) the marginal revenue conditions hold.⁵ $D'(\bar{q}) + \bar{x}D''(\bar{q}) \leq 0$ and $D'(\bar{q}) + \bar{y}D''(\bar{q}) \leq 0$.*

Proposition 3 *With conventional assumptions, we have the following comparative statics:*

i) $\partial \bar{q}/\partial \epsilon < 0$, $\partial \bar{p}/\partial \epsilon > 0$; that is, the price rises and industrial output falls with a wider technology gap;

ii) $\partial \bar{x}/\partial \epsilon < 0$, $\partial \bar{y}/\partial \epsilon > 0$.

Proposition 1 and 3 show that widening gap between the advanced and backward technologies leads to lower output for the price-takers at the equilibrium, higher output level for Cournot players, reduced overall output and higher market price. When such technological gap is small, backward firms outperform their advanced counterparts in terms of profits.

Theorem 4 *When conventional assumptions hold at the equilibrium, $\partial \bar{\pi}^y(x, y)/\partial \epsilon > 0$ holds for all ϵ . In contrast, there exists a $\tilde{\epsilon} > 0$ such that $\partial \bar{\pi}^x(x, y)/\partial \epsilon > 0$ for all $\epsilon \in [0, \tilde{\epsilon})$.*

In an extreme market structure like perfect competition or monopoly, given the choice, a profit maximizing firm would always choose the most efficient technology. Under heterogeneous oligopoly, however, Theorem 4 reveals a counterintuitive fact that a poor technology might be

⁵Marginal revenue condition implies the expected marginal revenues of firms do not decline slower than the price at the equilibrium. See Frank (1965) and Ruffin (1971) for details.

favored by the backward firms, as there exist the possibilities that wider technological gap may result in bigger profits for both type of firms. The advanced Cournot players would always benefit when they pursue technological advancement. When the technological gap is sufficiently small, the backward price-takers may deliberately deviate from the most cost-efficient technology available as the more inferior a technology they adopt, the higher profit they are able to obtain. That said, catching up and closing the technological gap with the industry leader is demotivating.

To explain the rationale of the equilibrium in which a more inferior technology is preferred, two effects are identified following a wider technological gap, *cost effects* and *strategic effects*. The former represents the immediate impact that, *ceteris paribus*, when a more inferior technology is adopted, profits fall for the backward firms. The latter captures the indirect effects of a wider gap on the total output in the oligopoly, the equilibrium price level and the consequent profit. An increase in ϵ leads to a smaller quantity produced by the oligopoly and hence allows a higher market price, which in turn results in a higher profit level. When the strategic effect outweighs the cost effect, wider technological gap causes an increase in the profit realized by the backward. The impacts of these two effects will be further addressed in Section 3.

2.2 Impact of technology gap on society

In this part, we consider the social impact of technology gap. In particular we focus on the effect of technological gap on the level of market concentration and competition, as well as social welfare. To investigate the impact of technological gap ϵ on the concentration of market, consider the Hirschman-Herfindahl Index (HHI) at an equilibrium defined by

$$H = \sum (s^i)^2 = m(s^y)^2 + (N - m)(s^x)^2$$

where $s^h(\cdot) = h/\bar{q}$, $h = x, y$, is the market share of each advanced or backward firm.

Theorem 5 *When conventional assumptions hold at the equilibrium, $\partial H/\partial \epsilon \geq 0$ if $\bar{y} \geq \bar{x}$. Equivalently, there exists a $\epsilon^\# > 0$ such that $\partial H/\partial \epsilon < 0$ for all $\epsilon \in [0, \epsilon^\#)$.*

It follows that we have $\partial H/\partial \epsilon < 0$ for all $\epsilon \in [0, \epsilon^*)$, where ϵ^* is specified in Proposition 1. It is worth pointing out that $[0, \epsilon^*)$ is a subset of $[0, \epsilon^\#)$ in which $\bar{y} < \bar{x}$ is satisfied, as evidenced by the graphical analysis in the next section.

Theorem 5 implies that, for certain range of technological gap, widening technological gap essentially leads to lower level of market concentration and higher level of market competition. It thus intrigues us to explore further its welfare implications.

To avoid complications induced by income and distributional effects, we assume the consumption of this good is by a representative consumer. Hence total welfare is defined as the sum of consumer and producer surpluses. In other words, the social welfare at equilibrium is measured by

$$\begin{aligned} W(\epsilon) &\doteq \int_0^{\bar{q}} D(q) dq - mC(\bar{y}) - (N-m)(1+\epsilon)C(\bar{x}) \\ &= \int_0^{(N-m)\bar{x}+m\bar{y}} D(q) dq - mC(\bar{y}) - (N-m)(1+\epsilon)C(\bar{x}) \end{aligned}$$

which will be a function of ϵ .

Theorem 6 *When conventional assumptions hold at the equilibrium, there exists a $\hat{\epsilon} > 0$ such that $\partial W / \partial \epsilon > 0$ for some $\epsilon > \hat{\epsilon}$, that is, wider technological gap will be social welfare improving.*

The intuition could be as follows. When the gap between the advanced and backward firms is larger than some critical value and continue to widen, the former increase their output while the latter cut the production. With higher market price following lower industrial output, consumer surplus decreases as a result. In the meanwhile, the advanced firms make higher profit while the backward players make less. When the overall increase in producer surplus more than offsets the decrease in consumer surplus, the total welfare enhances with a wider gap between the leader and laggard. This result is interesting which implies the possibility that wider gap can be in fact welfare-enhancing so that a welfare-maximizing policy-makers may not always have the incentive to promote technological catch-up for the backwards to upgrade. A summary of comparative statics is provided in Table 1 below with threshold value of parameters in the Appendix A.1.

Table 1: Comparative Statics of technology gap

	$\bar{x}$	$\bar{y}$	$\bar{p}$	$\bar{q}$	$\bar{\pi}^x$	$\bar{\pi}^y$	H	W
$\frac{\partial}{\partial \epsilon}$	-	+	+	-	+ when $\epsilon < \tilde{\epsilon}$	+	- when $\epsilon < \epsilon^*$	+ when $\epsilon > \hat{\epsilon}$

3 A Linear Economy

Consider a linear economy⁶ with market demand $D(Q) = 100 - Q$ and quadratic cost $C(q) = q^2/10 + 4q$. We report simulation results in Table 2 with the assumption of $N = 15$. We found

⁶Linear market demand and linear supply (marginal cost)

that: i) π^y increases with ϵ , π^x increases with ϵ for small value of m and ϵ ; ii) $0 < m < 15$, $\partial H/\partial \epsilon < 0$ for $\epsilon < \epsilon^*$, and ϵ^* is independent of m , and iii) $\partial W/\partial \epsilon > 0$ when ϵ is larger than $\hat{\epsilon}$.

The simulation implies that for a given m and ϵ that are sufficiently small, wider technological gap will be profit-enhancing for both advanced and backward firms (Fig 1). Meanwhile, when the gap is sufficiently small, market concentration will decrease with bigger gap and the critical value of the gap happens to be independent of m in this particular case (Fig 2). Moreover, wider gap can be beneficial to welfare when the technological gap is greater than certain critical value (Fig 3). In Fig 4 below we illustrate the partition of the (m, ϵ) parameter space into regions where bigger technological gap is preferred or unfavored. Particularly, the dividing lines of $\tilde{\epsilon}$, $\epsilon^\#$ and $\hat{\epsilon}$ show the segmentation of the (m, ϵ) space into regions where wider technological gap is preferred when profits of backward firm, market concentration and social welfare are concerned respectively. Note that ϵ^* is the line of equal profits for the advanced and the backward firms.

As depicted in Fig 4, the value of $\tilde{\epsilon}$, $\epsilon^\#$ and $\hat{\epsilon}$ vary with the number of advanced firm in the oligopoly, m . Specifically, the line $\tilde{\epsilon}$ shows, given different m , the magnitude of ϵ under which $\partial \bar{\pi}^x(x, y)/\partial \epsilon > 0$ is satisfied. Put it differently, the area below the $\tilde{\epsilon}$ line shows the possibility where a wider technological gap is preferred by the backward firm for such wider gap results in higher absolute profits. Under this circumstance, deliberate deviation from technology leader in the industry generates, through the interaction with the advanced leaders, a strategic effect which outplays the direct cost effect immediately following a more inferior technology, rendering sweeter profits for the backward. To be specific, the direct cost effect is negative which is captured by $-C(\bar{x}) = -0.1\bar{x}^2 - 4\bar{x}$, whereas the strategic effect can be expressed as $-\beta_2(N - m)\bar{x}D'/\Delta = 3(6\epsilon + 5m\epsilon - 25m + 456)^{-1}(15 - m)(2x + 40)\bar{x}$, according to the proof of Theorem 4. When the overall effects are positive, backward firms stand to gain from a wider technological gap in the oligopoly.

Similarly, the line ϵ^* is the dividing line when relative profits between the advanced and the backward are concerned. Below the line ϵ^* is the combination of m and ϵ where $\bar{\pi}^x(x, y) > \bar{\pi}^y(x, y)$, or, the backward outperforms their advanced counterparts in terms of profits; whereas the area above ϵ^* shows the opposite possibility. In addition, the line $\epsilon^\#$ in Fig 4 shows the combination of m and ϵ where the outputs of firms from respective category are equal. When technological gap is smaller than $\epsilon^\#$, each backward firm produces a higher level of output compared with the output level of the advanced. Based on Theorem 5, this area is also where $\partial H/\partial \epsilon < 0$ is satisfied, implying a wider technology gap will lead to lower market concentration and hence higher competition. Lastly, the line $\hat{\epsilon}$ is indicative of the combination of m and ϵ

Table 2: Simulation Results of Catching-up

m	$\epsilon=0$						$\epsilon=0.5$						$\epsilon=1$						$\epsilon=1.5$						$\epsilon=2$						$\epsilon=2.5$					
	π^x	π^y	H	W	π^x	π^y	H	W	π^x	π^y	H	W	π^x	π^y	H	W	π^x	π^y	H	W	π^x	π^y	H	W	π^x	π^y	H	W	π^x	π^y	H	W	π^x	π^y	H	W
0	4.0	-	6.7	4547	5.7	-	6.7	4331	7.1	-	6.7	4122	8.4	-	6.7	3919	9.5	-	6.7	3723	10.5	-	6.7	3533												
1	4.5	1.4	7.0	4544	6.0	11.6	6.8	4337	7.2	31.4	6.7	4146	8.1	59.8	6.7	3971	8.7	96.4	6.9	3811	9.0	140.4	7.2	3665												
2	5.0	1.5	7.3	4541	6.5	12.0	6.9	4343	7.4	31.5	6.7	4170	7.8	59.0	6.7	4022	7.8	93.6	7.1	3896	7.6	134.4	7.7	3790												
3	5.7	1.7	7.7	4538	7.0	12.5	7.0	4349	7.5	31.8	6.7	4195	7.4	58.2	6.8	4072	7.0	90.7	7.3	3977	6.2	128.2	8.2	3908												
4	6.5	2.0	8.2	4534	7.6	13.0	7.1	4355	7.6	32.0	6.7	4220	7.1	57.3	6.8	4121	6.1	87.6	7.5	4055	4.9	121.8	8.6	4017												
5	7.6	2.3	8.6	4530	8.3	13.6	7.3	4362	7.8	32.2	6.7	4245	6.7	56.3	6.8	4169	5.2	84.3	7.6	4128	3.7	115.2	9.0	4118												
6	8.9	2.7	9.2	4525	9.1	14.3	7.4	4369	8.0	32.5	6.7	4270	6.3	55.2	6.9	4216	4.4	80.8	7.8	4198	2.6	108.3	9.3	4209												
7	10.5	3.2	9.8	4520	10.1	15.2	7.6	4377	8.2	32.9	6.7	4295	5.8	54.0	6.9	4261	3.5	77.1	7.9	4262	1.6	101.3	9.6	4291												
8	12.7	3.9	10.4	4514	11.3	16.2	7.7	4385	8.4	33.2	6.7	4321	5.3	52.7	6.9	4304	2.7	73.3	8.0	4321	0.9	94.0	9.7	4363												
9	15.5	4.7	11.1	4508	12.8	17.4	7.9	4395	8.7	33.7	6.7	4348	4.8	51.3	6.9	4345	1.9	69.1	8.1	4374	0.3	86.6	9.8	4424												
10	19.5	6.0	11.9	4501	14.7	18.9	8.0	4406	9.0	34.2	6.7	4375	4.3	49.7	7.0	4385	1.2	64.8	8.1	4420	0.02	78.9	9.7	4473												
11	25.3	7.7	12.7	4494	17.3	20.8	8.1	4419	9.4	34.7	6.7	4403	3.7	48.0	7.0	4421	0.6	60.1	8.0	4460	0.1	71.0	9.5	4510												
12	34.1	10.4	13.3	4488	20.7	23.3	8.2	4435	9.9	35.4	6.7	4432	3.1	46.1	6.9	4455	0.2	55.2	7.9	4491	0.6	63.0	9.2	4535												
13	48.3	14.8	13.6	4484	25.5	26.7	8.1	4456	10.4	36.3	6.7	4463	2.5	43.9	6.9	4485	0.006	50.0	7.6	4514	1.7	54.9	8.6	4547												
14	73.8	22.6	12.5	4491	32.5	31.5	7.7	4485	11.2	37.3	6.7	4495	1.9	41.4	6.8	4510	0.1	44.4	7.2	4527	3.4	46.8	7.8	4546												
15	-	38.6	6.7	4530	-	38.6	6.7	4530	-	38.6	6.7	4530	-	38.6	6.7	4530	-	38.6	6.7	4530	-	38.6	6.7	4530												

Note: Values of H are in percentage

above which $\partial W/\partial \epsilon > 0$ is satisfied, i.e., to the right (left) of $\hat{\epsilon}$ line lies the area where wider gap is welfare enhancing (deteriorating).

Based on the relative magnitudes of special values of ϵ , the following possibilities exist:

1. $\hat{\epsilon} > \tilde{\epsilon} > \epsilon^\# > \epsilon^*$, which occurs when $0 < m \leq 3$. Under this circumstance, for $0 < \epsilon < \tilde{\epsilon}$, backward firm's profit increases with ϵ , implying an incentive to deviate from industrial leader as wider gap gives rise to higher profits. Within the range of $(0, \epsilon^\#)$, larger technological gap between the advanced and backward will bring about lower market concentration and higher competition. Particularly when $\epsilon \in (0, \epsilon^*)$, backward firms make higher profit than the advanced and in the meantime stand to benefit from a wider technological gap which results in higher absolute profit and lower market concentration.
2. $\hat{\epsilon} > \epsilon^\# > \tilde{\epsilon} > \epsilon^*$, which occurs when $4 \leq m \leq 5$. Market competition level increases with the technological gap in the oligopoly when $\epsilon < \epsilon^\#$. Meanwhile, when $0 < \epsilon < \tilde{\epsilon}$ is satisfied in particular, backward firms' profit also rise in tandem with a wider gap between the technology pioneer and laggard. Specifically, backward firms make more profit than advanced firms when ϵ is below ϵ^* .
3. $\hat{\epsilon} > \epsilon^\# > \epsilon^* > \tilde{\epsilon}$, which occurs when $6 \leq m \leq 8$. When ϵ falls into the area $(0, \tilde{\epsilon})$, not only backward firms outperform the advanced firms in terms of profit, they also prefer more inferior technology which leads to higher profit and less market concentration.
4. $\epsilon^\# > \hat{\epsilon}$, which occurs when $10 \leq m \leq 14$. When ϵ falls into the area $(\hat{\epsilon}, \epsilon^\#)$, bigger ϵ leads to not only higher market competition but also enhanced welfare, suggesting the disincentive to catch up from a social perspective. In this scenario, backward firms make less profit compared with the advanced firms when $m < 14$.

4 Concluding Remarks

Common sense suggests that a competitive firm that does not use the most efficient technology will be driven out of business by firms that do. In contrast to this, we document a seemingly paradoxical phenomena where an increase in technological gap between the advanced and the backward group can be profit-enhancing for both. Technology leader sensibly has the incentive to pursue more advanced production technique to strengthen its leadership. When it does so, the backward followers may not always find it motivating to catch up in the technological race. This finding is consistent with the results of Pérez and Ponce (2015) that confirms cases when

Figure 1: Technological Gap and Profits

the adoption of Pareto superior technologies is unprofitable and that the adopting firm prefers to stick to an old technology rather than to switch to a better one. When market concentration and social welfare are concerned, widening gap can lead to higher level of market competition and enhanced welfare. This echoes the findings of Milliou and Petrakis (2011) that in certain cases the speed of new technology adoption is too fast from a welfare perspective. Our results can help explain why different technologies coexist in a homogenous goods market and shed some lights on the rationale of relatively inferior technology deliberately adopted by some oligopolist producers.

It is found that wider technological gaps in oligopoly may surprisingly be profit enhancing for both groups and also desirable from a social perspective. Therefore, backward firms have no incentive to catch up. Our model can provide some theoretical ground on the postponement in the diffusion of and the strategic timing of the adoption of new technologies. One limitation of this study lies in the assumption of the existence of an unique equilibrium. Focusing on equilibrium analysis, we provide some counterintuitive results that may stimulate future exploration of

Figure 2: Technological Gap and Market Concentration

Cournot oligopoly with stricter rigor. One possible extension is to explore endogenously varying market structure.

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Figure 3: Technological Gap and Social Welfare

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Figure 4: Partition of the (m, ε) space into regions where wider technological gap is preferred or disfavored.

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Appendix

A.1 Parameters

The exact values of parameter ϵ and m

Location	Parameter
Proposition 1	$\epsilon^\# = -\bar{y}(\epsilon^\#) D' / C'(\bar{y}(\epsilon^\#))$
	$\epsilon^* = -1 + C(\bar{y}(\epsilon^*)) / [C(\bar{x}(\epsilon^*)) - C'(\bar{x}(\epsilon^*))(\bar{x}(\epsilon^*) - \bar{y}(\epsilon^*))] > 0$
Theorem 4	$\tilde{\epsilon} = -1 + \frac{(N-m)(D' - C''(\bar{y}))(C(\bar{x}) - C'(\bar{x})\bar{x})D'}{C(\bar{x})C''(\bar{x})((m+1)D' - C''(\bar{y}) + m\bar{y}D'')} > 0$
Theorem 6	$\hat{\epsilon} = -1 + D' \frac{(N-m)^2 C(\bar{x})(D' - C''(\bar{y})) - m\bar{y}C'(\bar{x})(D' + \bar{y}D'')}{C(\bar{x})C''(\bar{x})[(D' - C''(\bar{y})) + m(D' + \bar{y}D'')]} > 0$

A.2 Derivation and Proofs

Proof of Proposition 1

Subtracting (1) from (2) gives

$$(1 + \epsilon)C'(\bar{x}(\epsilon)) - C'(\bar{y}(\epsilon)) = -\bar{y}(\epsilon) D'. \quad (3)$$

When $\bar{x}(\epsilon^\#) = \bar{y}(\epsilon^\#)$ at equilibrium, Eq.(3) reduces to $-\bar{y}(\epsilon^\#) D' = \epsilon^\# C'(\bar{x}(\epsilon^\#)) = \epsilon^\# C'(\bar{y}(\epsilon^\#))$, which suggests that $\epsilon^\# = -\bar{y}D' / C'(\bar{y})$.

The RHS of Eq.(3) is always positive. When $\epsilon = 0$, Eq.(3) degenerates to $C'(\bar{x}) - C'(\bar{y}) = -\bar{y}D'$, which implies $\bar{x}(0) > \bar{y}(0)$.

When $\epsilon = \epsilon^*$, we have

$$(1 + \epsilon^*)C'(\bar{x}(\epsilon^*)) = \frac{(1 + \epsilon^*)C(\bar{x}(\epsilon^*)) - C(\bar{y}(\epsilon^*))}{\bar{x}(\epsilon^*) - \bar{y}(\epsilon^*)}.$$

Consequently, the LHS of (3) becomes

$$\begin{aligned} & \frac{(1 + \epsilon^*)C(\bar{x}(\epsilon^*)) - C(\bar{y}(\epsilon^*))}{\bar{x}(\epsilon^*) - \bar{y}(\epsilon^*)} - C'(\bar{y}(\epsilon^*)) \\ &= \frac{\epsilon^*}{\bar{x}(\epsilon^*) - \bar{y}(\epsilon^*)}C(\bar{x}(\epsilon^*)) + \frac{C(\bar{x}(\epsilon^*)) - C(\bar{y}(\epsilon^*))}{\bar{x}(\epsilon^*) - \bar{y}(\epsilon^*)} - C'(\bar{y}(\epsilon^*)), \end{aligned}$$

which is positive iff $\bar{x}(\epsilon^*) > \bar{y}(\epsilon^*)$. The facts that $\bar{x}(0) > \bar{y}(0)$, $\bar{x}(\epsilon^*) > \bar{y}(\epsilon^*)$ and the monotonic properties exhibited by $\bar{x}(\epsilon)$ and $\bar{y}(\epsilon)$ suggest that for all $\epsilon \in [0, \epsilon^*)$, $\bar{x}(\epsilon) > \bar{y}(\epsilon)$. Hence $\epsilon^* < \epsilon^\#$. ■

Proof of Proposition 3

i) Total differentiation of first order conditions (1) and (2) leads to

$$\begin{cases} (D' + \bar{y}D'')(\partial\bar{q}/\partial\epsilon) + (D' - C''(\bar{y}))(\partial\bar{y}/\partial\epsilon) = 0 \\ D'(\partial\bar{q}/\partial\epsilon) - (1 + \epsilon)C''(\bar{x})(\partial\bar{x}/\partial\epsilon) - C'(\bar{x}) = 0 \end{cases}.$$

Let $\alpha_1 = \frac{D' + \bar{y}D''}{D' - C''(\bar{y})} > 0$, $\alpha_2 = \frac{D'}{-(1 + \epsilon)C''(\bar{x})} > 0$, and $\beta_2 = \frac{C'(\bar{x})}{(1 + \epsilon)C''(\bar{x})} > 0$, we have⁷

$$\begin{cases} \alpha_1(\partial\bar{q}/\partial\epsilon) + (\partial\bar{y}/\partial\epsilon) = 0 \\ \alpha_2(\partial\bar{q}/\partial\epsilon) + (\partial\bar{x}/\partial\epsilon) + \beta_2 = 0 \end{cases}$$

Combining these two equations yields:

$$(1 + m\alpha_1 + (N - m)\alpha_2)(\partial\bar{q}/\partial\epsilon) + (N - m)\beta_2 d\epsilon = 0.$$

Hence,

$$\partial\bar{q}/\partial\epsilon = -\frac{(N - m)\beta_2}{\Delta} \quad (4)$$

where $\Delta = 1 + m\alpha_1 + (N - m)\alpha_2$. It follows that: $\partial\bar{q}/\partial\epsilon < 0$. Moreover, $\partial\bar{p}/\partial\epsilon = D'(\partial\bar{q}/\partial\epsilon) > 0$.

ii) Partially differentiate the first order conditions (1) and (2) with respect to ϵ , we have

$$\begin{cases} (D' + \bar{y}D'')(\partial\bar{q}/\partial\epsilon) + D'(\partial\bar{y}/\partial\epsilon) = C''(\partial\bar{y}/\partial\epsilon) \\ D'(\partial\bar{q}/\partial\epsilon) = C'(\bar{x}) + (1 + \epsilon)C''(\partial\bar{x}/\partial\epsilon). \end{cases}$$

⁷Here β_2 can be interpreted as the multiplication of its output and the elasticity of backward firm's competitive supply curve. See Dung (1993).

or, more compactly

$$\begin{cases} -\alpha_1(\partial\bar{q}/\partial\epsilon) = (\partial\bar{y}/\partial\epsilon) \\ -\alpha_2(\partial\bar{q}/\partial\epsilon) = \beta_2 + (\partial\bar{x}/\partial\epsilon). \end{cases}$$

Hence, $\partial\bar{y}/\partial\epsilon = (N - m)\alpha_1\beta_2/\Delta > 0$; and $\partial\bar{x}/\partial\epsilon = -(1 + m\alpha_1)\beta_2/\Delta < 0$. ■

Proof of Theorem 4

From (2), direct differentiation leads to

$$\begin{aligned} \partial\bar{\pi}^y(x, y)/\partial\epsilon &= (D - C'(\bar{y}))(\partial\bar{y}/\partial\epsilon) + \bar{y}D'(\partial\bar{q}/\partial\epsilon) \\ &= -\bar{y}D'(\bar{q})(\partial\bar{y}/\partial\epsilon) + \bar{y}D'(\bar{q})(\partial\bar{q}/\partial\epsilon) \\ &= (\alpha_1 + 1)\bar{y}D'(\bar{q})(\partial\bar{q}/\partial\epsilon) > 0 \end{aligned}$$

Given $D = (1 + \epsilon)C'(\bar{x})$, we have

$$\begin{aligned} \partial\bar{\pi}^x(x, y)/\partial\epsilon &= D(\partial\bar{x}/\partial\epsilon) + \bar{x}D'(\partial\bar{q}/\partial\epsilon) - (1 + \epsilon)C'(\bar{x})(\partial\bar{x}/\partial\epsilon) - C(\bar{x}) \\ &= (\partial\bar{q}/\partial\epsilon)\bar{x}D' - C(\bar{x}) \\ &= -C(\bar{x}) - \beta_2(N - m)\bar{x}D'/\Delta \end{aligned}$$

which is positive when $m < N - C(\bar{x})\Delta/\beta_2\bar{x}D'$; put differently, $\partial\bar{\pi}^x(x, y)/\partial\epsilon > 0$ when

$$0 < \epsilon < \tilde{\epsilon} = -1 + \frac{(N - m)D'(D' - C''(\bar{y}))(C(\bar{x}) - C'(\bar{x})\bar{x})}{C(\bar{x})C''(\bar{x})((m + 1)D' - C''(\bar{y}) + m\bar{y}D'')}. \blacksquare$$

Proof of Theorem 5

Following the definition of HHI, we have

$$\begin{aligned} \partial H/\partial\epsilon &= 2ms^y(\partial s^y/\partial\epsilon) + 2(N - m)s^x(\partial s^x/\partial\epsilon) \\ &= 2ms^y[(\partial\bar{y}/\partial\epsilon) - s^y(\partial\bar{q}/\partial\epsilon)]/\bar{q} + 2(N - m)s^x[(\partial\bar{x}/\partial\epsilon) - s^x(\partial\bar{q}/\partial\epsilon)]/\bar{q} \\ &= 2\beta_2(N - m)[ms^y\alpha_1 + ms^y s^y - (1 + m\alpha_1)s^x + s^x(N - m)s^x]/\bar{q}\Delta \\ &= 2\beta_2(N - m)m(s^y + \alpha_1)(s^y - s^x)/\bar{q}\Delta. \end{aligned}$$

It indicates that $\partial H/\partial\epsilon$ has the same sign as $(s^y - s^x)$, or equivalently, $(\bar{y} - \bar{x})/\bar{q}$. Hence, when $\epsilon \in [0, \epsilon^\#)$, $\partial H/\partial\epsilon < 0$. ■

Proof of Theorem 6

Following the definition of W , we have

$$\begin{aligned}
\partial W / \partial \epsilon &= D(\bar{q})(\partial \bar{q} / \partial \epsilon) - [mC'(\bar{y})(\partial \bar{y} / \partial \epsilon) + (N-m)(1+\epsilon)C'(\bar{x})(\partial \bar{x} / \partial \epsilon)] - (N-m)C(\bar{x}) \\
&= m(\partial \bar{y} / \partial \epsilon) [C'(\bar{y}) - \bar{y}D'(\bar{q}) - C'(\bar{y})] - (N-m)C(\bar{x}) \\
&= -(N-m)C(\bar{x}) - m\bar{y}D'(\bar{q})(N-m)\alpha_1\beta_2/\Delta \\
&= -(N-m) [C(\bar{x}) + m\bar{y}D'(\bar{q})\alpha_1\beta_2/\Delta]
\end{aligned}$$

The critical value(s) for $\partial W / \partial \epsilon = 0$ is (are) $\hat{\epsilon} = -1 + D' \frac{(N-m)^2 C(\bar{x})(D' - C''(\bar{y})) - m\bar{y}C'(\bar{x})(D' + \bar{y}D'')}{C(\bar{x})C''(\bar{x})[(D' - C''(\bar{y})) + m(D' + \bar{y}D'')]} ,$ which leads to Theorem 6. ■

A.3 The Model

For tractability, we will work with a well-behaved Cournot oligopoly with the following technical assumption. Consider N firms producing q_t^i , $i = 1, 2, \dots, N$, at period t in an homogeneous oligopoly market with inverse demand function $p_t = D(q_t^d)$ with $D' \leq 0$. For every $q_t^d = \sum_{i=1}^N q_t^i$ supplied to the market, this function specifies the market-clearing price. Firms are grouped into two categories; the first m firms belong to the advanced category and the remaining $(N-m)$ firms the backward.

We further consider the choice among some convex technologies which can be ranked in terms of efficiency; for all positive quantities, costs are strictly lower for some technology than they are for others. All advanced firms are assumed to have the same differentiable cost functions $c_i(q) = C(q)$, $i = 1, 2, \dots, m$ and adopt the sophisticated Cournot production strategy to maximize the expected profit $\pi^y = \hat{p}_t y_t - C(y_t)$, which leads to an implicitly determined output y_t :

$$\begin{aligned}
D((m-1)y_{t-1} + (N-m)x_t + y_t) + y_t \frac{dD}{dy_t} &= C'(y_t) \\
\text{or } \hat{p}_t + y_t \frac{d\hat{p}_t}{dy_t} &= C'(y_t). \tag{5}
\end{aligned}$$

where $\hat{p}_t$ and $d\hat{p}_t/dy_t$ depend on the current and historical data $\{p_{t-s}, x_{t-s}, y_{t-s}\}_{s=0}^t$. Here x_t is the identical output level of the backward firms with poorer technology and cost function $c_j(q) = (1+\epsilon)C(q)$, for $j = m+1, m+2, \dots, N$, where $\epsilon \geq 0$, referred to as the inefficiency parameter. The backward will act as price-takers with naive price expectations $\hat{p}_{j,t} = p_{t-1}$, choose their production level by setting $p_{t-1} = MC_t^j$ and produce x_t in accordance with the following.

$$\begin{aligned}
D(my_{t-1} + (N - m)x_{t-1}) &= (1 + \epsilon)C'(x_t) \\
\text{or } p_{t-1} &= (1 + \epsilon)C'(x_t) .
\end{aligned} \tag{6}$$

Equations (5) and (6) together form a discrete dynamic process:

$$\begin{aligned}
x_t &= f^x(x_{t-1}, y_{t-1}) \\
y_t &= f^y(x_{t-1}, x_{t-2}, \dots, y_{t-1}, y_{t-2}, \dots)
\end{aligned} \tag{7}$$

where $f^q(\cdot)$, $q = x, y$, denotes the reaction functions for the backward and the advanced respectively.