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Product differentiation, process R&D, and the nature of market competition

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Abstract

We investigate the relationship between process and product R&D and compare the incentives for both types of R&D under different modes of market competition (Bertrand versus Cournot). It is shown that: (i) process R&D investments increase with the degree of product differentiation and firms invest more in product R&D when they can do process R&D than when they cannot; (ii) Bertrand firms have a stronger incentive for product R&D whereas Cournot firms invest more in process R&D; and (iii) cooperation in product R&D promotes both types of R&D relative to competition whereas cooperation in both types of R&D discourages R&D relative to cooperation in just product R&D.

JEL classification: L13; O32

Keywords: Product R&D; Process R&D; Complementarity

1. Introduction

Most of the rather large theoretical literature on R&D focuses on process innovation. However, this focus is striking given the fact that approximately three-fourths of R&D investments by firms in the United States are devoted to

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product R&D (Scherer and Ross, 1990). In contrast to the theoretical literature, product R&D and its relationship to process R&D have drawn considerable attention in empirical studies. For example, Mansfield (1981), Scherer (1991), and Cohen and Klepper (1996) analyze how market concentration and firm size influence the choice between product and process R&D. Our goal in this paper is to contribute to the theoretical development of this line of research. In particular, we explore the linkages between the two types of R&D and shed light on the dependence of these linkages on the nature of product market competition.

Building upon previous work by Dixit (1979) and Singh and Vives (1984), we construct a duopoly model comprised of three stages. In the first stage, firms choose their investments in product R&D. These product R&D investments determine the degree of differentiation between their products. In the second stage, they choose their investments in process R&D. Product market competition takes place in the final stage.[1] In our model, both product and process R&D affect firm profitability through the price–cost margin. While process R&D enlarges the price–cost margin by reducing the marginal cost of production, product R&D allows firms to charge higher prices by increasing consumer willingness to pay for their products. Since total profit equals output times the price–cost margin, the larger a firm's output, the more attractive is either form of R&D to the firm. This *output effect* leads to a two-way complementarity between the two types of R&D. First, product R&D increases demand for the products of both firms. This increased demand raises the equilibrium output levels and thus enhances their returns from process R&D (see also Athey and Schmutzler, 1995). Second, process R&D also increases equilibrium output levels by lowering costs of production and therefore makes product R&D more attractive.

Using this complementarity property, we obtain the following results. First, the equilibrium level of process R&D investment increases with the degree of product differentiation. Second, firms invest more in product R&D when they can do process R&D than when they cannot. Third, while cooperation in product R&D increases investments in both types of R&D, cooperation in process R&D discourages both types of R&D. Consequently, cooperation in product R&D enhances social welfare relative to competition whereas cooperation in both types of R&D lowers welfare relative to cooperation in just product R&D.

We also find that Bertrand firms invest more in product R&D than Cournot firms. This result complements the existing finding that, given the extent of product differentiation, the incentive for process R&D is stronger under

[1] Our assumption regarding the sequential pattern of R&D (product R&D followed by process R&D) formalizes a stylized view of the life cycle of a typical product: After establishing their products in the market, firms then invest in process R&D to lower production costs. Empirical evidence supports such a formulation (see Klepper, 1996; Utterback and Abernathy, 1983).

Cournot competition than under Bertrand competition.[2] The reason this ranking is reversed under product R&D is as follows. While the strategic incentive for process R&D is positive for Cournot firms and negative for Bertrand firms, the strategic incentive for product R&D is actually negative for Cournot firms and positive for Bertrand firms. Thus, our results show that the *type* of R&D interacts in a non-obvious way with the *nature* of product market competition.

In a related paper, Rosenkranz (1996) develops a model where firms make *simultaneous* decisions regarding product and process innovations. The focus of her paper is on the optimal division of investment between the two types of R&D. Unlike us, Rosenkranz (1996) does not examine the interaction between process and product R&D. In fact, a sequential model may be better suited for studying this interaction. Furthermore, we also consider Bertrand competition, whereas Rosenkranz considers only Cournot competition. Using a linear demand system similar to the one employed in this paper, Vives (1990) analyzes a two-stage game where two duopolists first invest in improving their competitive position, and then compete in the product market.[3] In Vives' model, first-stage investments can be interpreted as either product or process R&D. However, Vives did not examine the interaction between the two types of R&D.[4]

2. Product differentiation only

Consider two firms that produce differentiated goods. The representative consumer's utility is a function of the consumption of the two differentiated goods and the numeraire good m and is given by

$$u(q_1, q_2, m) = a(q_1 + q_2) - (q_1^2 + q_2^2)/2 - sq_1q_2 + m, \quad 0 \le s \le 1. \tag{1}$$

Utility maximization gives rise to the following demand system:

$$p_1 = a - q_1 - sq_2 \quad \text{and} \quad p_2 = a - sq_1 - q_2, \tag{2}$$

where q_i is the output of firm i and p_i its price. The parameter s represents the degree of substitutability between the two products: Products are homogeneous

[2] This finding was reported by Qiu (1997), who considered process R&D only (see also Bester and Petrakis, 1993).

[3] In Vives (1990), product differentiation by a firm enhances the demand for its product but, unlike our model, it does not affect the demand for its rival's product.

[4] More recently, Bonanno and Haworth (1998) study incentives for product and process R&D under different modes of competition in a model of vertical (as opposed to horizontal) product differentiation. Firms are not allowed to conduct both types of R&D in their model.

if $s = 1$ and unrelated if $s = 0$. Note that an increase in the degree of product differentiation (a decline in s) shifts the demand curves for *both* firms outward.

The firms' investments in product R&D, denoted by d_i, determine the extent of product differentiation as follows: $s = \bar{s} - (d_1 + d_2)$, where $\bar{s}$ is the initial level of product substitutability and $0 \leq d_i \leq \bar{s}/2$. The cost of product R&D is given by $F(d_i)$, $F' > 0$, $F'' > 0$. To obtain interior solutions, we assume that $F'(0) = 0$ and $F'(\bar{s}/2)$ is very large. After simultaneously choosing their product R&D investments, firms compete in the product market. The marginal cost of production is constant and equals $c > 0$. Denote firm i's profit function as a Cournot competitor by $\pi_i^{\mathrm{C}}(s, q_i(s), q_j(s))$ where $q_i(s)$ and $q_j(s)$ represent the two firms' output levels. At the product R&D stage, firm i chooses d_i, taking d_j, $q_i(.)$, and $q_j(.)$ as given. By the envelope theorem, we have

$$\frac{\mathrm{d}\pi_i^{\mathrm{C}}}{\mathrm{d}d_i} = -\frac{\partial \pi_i^{\mathrm{C}}}{\partial s} - \frac{\partial \pi_i^{\mathrm{C}}}{\partial q_j}\frac{\mathrm{d}q_j}{\mathrm{d}s}. \tag{3}$$

An increase in d_i has two conflicting effects on firm i's profits. The direct effect (captured by the first term of Eq. (3)) is positive because an increase in the degree of product differentiation (i.e., a decline in s) shifts its own demand curve outward. However, the strategic effect (the second term of Eq. (3)) is negative because the demand curve facing firm j also shifts outward and the resulting increase in firm j's output hurts firm i.

Similarly, denote the profit function for Bertrand firms by $\pi_i^{\mathrm{B}}(s, p_i(s), p_j(s))$. We have

$$\frac{\mathrm{d}\pi_i^{\mathrm{B}}}{\mathrm{d}d_i} = -\frac{\partial \pi_i^{\mathrm{B}}}{\partial s} - \frac{\partial \pi_i^{\mathrm{B}}}{\partial p_j}\frac{\mathrm{d}p_j}{\mathrm{d}s}. \tag{4}$$

Under Bertrand competition, the strategic effect of an increase in d_i is positive: As firm i differentiates its product more, firm j raises its price and this price increase *benefits* firm i. Consequently, one expects Bertrand firms to invest more in product R&D than Cournot firms. For the demand system in (2), it is straightforward to show that the equilibrium profits for Cournot and Bertrand firms, respectively, are

$$\pi_i^{\mathrm{C}}(s) = \left(\frac{a-c}{2+s}\right)^2 \quad \text{and} \quad \pi_i^{\mathrm{B}}(s) = \frac{(1-s)}{(1+s)}\left(\frac{a-c}{2-s}\right)^2.$$

In the product R&D stage, firm i chooses d_i to maximize $\pi_i^k(s) - F(d_i)$, where, $k = \mathrm{C}, \mathrm{B}$. The first-order conditions for Cournot and Bertrand firms, respectively, are

$$\frac{2(a-c)^2}{(2+s)^3} = F'(d) \quad \text{and} \quad \frac{2(s^2-s+1)(a-c)^2}{(1+s)^2(2-s)^3} = F'(d), \tag{5}$$

where $s = \bar{s} - 2d$. Since $(s^2 - s + 1)(2 + s)^3 > (1 + s)^2(2 - s)^3$ for all $s \in (0, 1)$, it follows that the marginal benefit of product R&D is higher under Bertrand competition than under Cournot competition. We thus have the following result:

Proposition 1. The equilibrium level of product differentiation is higher under Bertrand competition than under Cournot competition.

3. Interaction between process and product R&D

In this section, we examine how the presence of process R&D alters the two firms' incentives for product R&D. To do this, we study a three-stage game. After choosing their product R&D investments, firms conduct process R&D and then compete in the product market. Process R&D investment by firm i, denoted by x_i, lowers its marginal cost from c to $c - x_i$. The cost function for process R&D is $\gamma(x_i)^2/2$, $\gamma > 0$. We assume that $\gamma \geq 8/9$ in order to guarantee that the second order condition for process R&D holds.[5]

First consider how process R&D investments depend on the degree of product substitutability s. For the demand system in Eq. (2), it is easy to derive the equilibrium levels of process R&D for Bertrand and Cournot firms (see footnote 5):

$$x^{\mathrm{B}}(s) = \frac{2(a-c)}{\gamma(1+s)(2+s)(2-s)^2/(2-s^2) - 2} \quad \text{and}$$

$$x^{\mathrm{C}}(s) = \frac{4(a-c)}{\gamma(2+s)^2(2-s) - 4}. \tag{6}$$

Proposition 2. (i) *Equilibrium process R&D investment under Bertrand competition strictly decreases with s, whereas under Cournot competition it decreases with s when* $s < 2/3$ *and increases when* $s > 2/3$. (ii) *Equilibrium process R&D investment is higher under Cournot competition* ($x^{\mathrm{B}} < x^{\mathrm{C}}$ *for all s*).

Part (i) of the above proposition highlights one side of the two-way complementarity between product and process R&D. Increased product differentiation shifts the demand curves of both firms outwards, thereby increasing their

[5] The corresponding second-order condition is $8/(4 - s^2)^2 \leq \gamma$ for Cournot firms, which holds for all s if $\gamma \geq 8/9$, and is $2(2 - s^2)^2/(1 - s^2(4 - s^2)^2 \leq \gamma$ for Bertrand firms, which holds for $0 < s < 0.8$ if $\gamma \geq 8/9$. These derivations and the proof of Proposition 2 can be found in Lin and Saggi (1999).

output levels and making cost-reducing R&D more attractive. As a result, equilibrium process R&D investments increase with the degree of product differentiation.[6]

Part (ii) of Proposition 2 can be understood in terms of the strategic effect of process R&D. Firm i's profits in the product market, as a Cournot competitor, can be written as $\pi_i^C(s, x_i, x_j, q_i, q_j)$. We have

$$\frac{\mathrm{d}\pi_i^C}{\mathrm{d}x_i} = \frac{\partial \pi_i^C}{\partial x_i} + \frac{\partial \pi_i^C}{\partial q_j}\frac{\partial q_j}{\partial x_i} \quad \text{for all } s. \tag{7}$$

An increase in x_i affects firm i's profits in two reinforcing ways. The direct effect (the first term of Eq. (7)) is positive because an increase in x_i lowers firm i's marginal cost. The strategic effect (the second term of Eq. (7)) is also positive because a reduction in its marginal cost enables firm i to steal market share from its rival. In contrast to Cournot firms, the strategic effect is actually negative for Bertrand firms and works against the direct effect. A reduction in firm i's marginal cost induces it to lower its price which in turn forces firm j to also lower its price. The price reduction by firm j undermines firm i's incentive for process R&D. As a result, Bertrand firms invest less in process R&D than Cournot firms (for any given s).[7]

Next, consider the product R&D stage. Let $x^*(s)$ denote the symmetric equilibrium level of process R&D derived in Proposition 2. Further, for Cournot firms, let $\prod_i(s, x_i, x_j) = \pi_i^C(s, x^*(s), x^*(s), q_i(\,.\,), q_j(\,.\,))$. For Bertrand firms, $\prod_i$ is defined as a function of equilibrium prices instead of quantities. Obviously, $\prod_i$ increases with x_i and decreases with both s and x_j.

Firm i chooses d_i to maximize $\prod_i(s, x^*(s), x^*(s)) - (\gamma/2)(x^*(s))^2 - F(d_i)$, where $s = \bar{s} - d_1 - d_2$. Since x_i is chosen optimally, the envelope theorem implies that the equilibrium level of product differentiation is determined by

$$-\frac{\partial \prod_i(s, x^*(s), x^*(s))}{\partial s} + \frac{\partial \prod_i(s, x^*(s), x^*(s))}{\partial x_j}\frac{\mathrm{d}x^*(s)}{\mathrm{d}s}(-1) = F'(d). \tag{8}$$

The first term of the above equation says that an increase in d_i raises firm i's profits (the direct effect). However, the second term of the above equation captures an indirect negative effect: an increase in d_i induces firm j to invest more in process R&D, hurting firm i in the product market. This negative effect

[6] If $s > 2/3$, process R&D increases with s for Cournot firms. This is because the strategic effect of process R&D, which is positive under Cournot competition, gets stronger for larger s. For a general oligopoly, it can be shown that the range over which process R&D increases with s shrinks as the number of firms increases.

[7] Note that this statement may not hold when s is chosen *endogenously*. This is because Bertrand firms invest more in product R&D which leads to more process R&D.

is absent if firms cannot do process R&D. However, the presence of process R&D strengthens the direct effect of product R&D.[8] For the linear demand system given in Eq. (2), we prove in the appendix that the direct positive effect outweighs the indirect negative effect so that the presence of process R&D strengthens the incentives for product R&D.

Proposition 3. Under both Bertrand and Cournot competition, firms invest more in product R&D when they can do process R&D than when they cannot.

4. R&D cooperation and welfare

We consider two scenarios in this section: Semi-cooperation whereby firms cooperate only in product R&D and full cooperation under which firms cooperate in both types of R&D. Thus, under either scenario, at the product R&D stage, firms choose a common investment level d to maximize the profit of each firm:

$$\max\left[\prod_i (s, x^*(s), x^*(s)) - \frac{\gamma}{2}(x^*(s))^2 - F(d)\right], \tag{9}$$

where $s = \bar{s} - 2d$. Under semi-cooperation, process R&D investments are the same as under competition, whereas under full cooperation these are chosen jointly.[9]

A positive externality exists between firms at the product R&D stage: Product differentiation by one firm also enhances demand for the other firm's product. Semi-cooperation internalizes this externality and thus increases product R&D relative to competition. By the complementarity property, process R&D increases as well. Under full cooperation, however, the well-known negative externality at the process R&D stage is also internalized. Thus, full cooperation lowers process R&D for all s. Less process R&D in turn implies less product R&D. We, therefore, have the following result:

[8] The first term of (8) is bigger when evaluated at $x_i = x^*(s) > 0$ (i.e., under optimal process R&D) than when evaluated at $x_i = 0$ (i.e., in the absence of process R&D).

[9] It is straightforward to show that the cooperative level of process R&D for Cournot firms is $x^{CC} = 2(a-c)/(\gamma(2+s)^2 - 2)$ and for Bertrand firms is

$$x^{BC} = \frac{2(a-c)}{\gamma(1+s)(2-s)^2/(1-s) - 2}.$$

These investments are smaller than their counterparts under R&D competition (see Lin and Saggi (1999) for details).

Proposition 4. Semi-cooperation promotes both types of R&D relative to competition. Full cooperation discourages both types of R&D relative to semi-cooperation.[10]

Another way of understanding the result regarding full cooperation is as follows. Let $\pi_f(s)$ denote the profit per firm at the product R&D stage under full cooperation and $\pi_s(s)$ under semi-cooperation. Two observations follow immediately. First, $\pi_f(s) > \pi_s(s)$ for all s because cooperation in process R&D necessarily raises profits. Second, the difference $\pi_f(s) - \pi_s(s)$ increases with s: The more similar the products, the stronger the magnitude of the negative externality at the process R&D stage, and thus larger the gain from R&D cooperation. Given that the derivative of $\pi_f(s) - \pi_s(s)$ is positive, we have $-(\mathrm{d}/\mathrm{d}s)\pi_f(s) < -(\mathrm{d}/\mathrm{d}s)\pi_s(s)$. Therefore, the marginal benefit of product R&D is lower under full cooperation than under semi-cooperation.

We next examine the welfare effects of R&D cooperation, starting with the case of semi-cooperation. We focus on Cournot competition (where cleaner results are possible) and comment on the Bertrand case whenever appropriate. In the symmetric equilibrium, consumer utility as given in Eq. (1) simplifies to $u = u(q, q, I - pq - pq) = (1 + s)q^2 + I$, where I is the consumer's endowment of the numeraire good. Under Cournot competition, we have $u = (1 + s)((a - c + x_{\mathrm{C}})/(2 + s))^2 + I$ which, by Eq. (6), is proportional to the market size parameter $(a - c)^2$. Thus, only the process R&D cost parameter, γ, determines how consumer surplus varies with s. Since algebraic complexity did not permit analytical derivations, we conducted numerical simulations to investigate the dependence of consumer welfare on s and γ. Table 1 contains representative results from our various simulations. It reports how consumer surplus (multiplied by $100/(a - c)^2$) varies with γ and s.

When $\gamma = 1$, consumer surplus initially decreases and then increases with s (for $s > 0.8$). Similarly, for $\gamma = 2$, simulations show that consumer surplus reaches a minimum at $s = 0.97$. However, when γ is larger ($\gamma = 3, 4$ in Table 1), consumer surplus *always* declines with s. In fact, our simulation results show that consumer surplus decreases with s for all $\gamma > 2.23$. We can, thus, conclude that semi-cooperation improves welfare for $\gamma > 2.23$: Semi-cooperation necessarily benefits firms and since it lowers s, it also makes consumers better off.[11] The relationship between consumer surplus and s (as reported in Table 1) can be understood as follows. First note that in the absence of process R&D ($x_{\mathrm{C}} = 0$), consumer welfare always decreases with s under Cournot competition. Despite

[10] Since full cooperation internalizes both externalities, its total effect on R&D depends upon the relative magnitudes of the two externalities. In general, relative to competition, full cooperation may either promote or hamper R&D.

[11] If products are initially not very similar (if $\bar{s} < 0.8$), or if product R&D cost is low (so that the equilibrium s is very small), semi-cooperation improves welfare even for small γ.

Table 1
Consumer surplus under Cournot competition

	$s=0.1$	$s=0.2$	$s=0.3$	$s=0.4$	$s=0.5$	$s=0.6$	$s=0.7$	$s=0.8$	$s=0.9$
$\gamma=1$	91.3	84.8	79.7	75.9	73.0	71.0	69.8	69.5	70.1
$\gamma=2$	43.0	41.8	40.6	39.6	38.8	38.1	37.5	37.0	36.8
$\gamma=3$	35.3	34.6	33.9	33.2	32.6	32.1	31.6	31.1	30.8
$\gamma=4$	32.1	31.6	31.1	30.6	30.1	29.6	29.1	28.7	28.4

increased prices, consumers benefit from a decrease in s because they value product differentiation and because output of both firms increases as s falls. Why does the presence of process R&D raise the possibility that consumers lose from an increase in product differentiation, especially when s is large and γ is small? From Section 3, we know that the strategic effect of process R&D under Cournot competition is quite strong when s is large. Hence, if s is large and if process R&D is not costly (i.e., γ is not big), an increase in s induces firms to invest a lot more in R&D, significantly lowering prices and thus raising consumer welfare. When γ is large, however, the increase in process R&D caused by an increase in s is insufficient to counter the decline in consumer surplus that results from the reduction in the degree of product differentiation.[12] Consequently, consumer welfare always decreases with s when γ is large.[13]

How does full cooperation affect social welfare? The fact that consumer surplus decreases with s (for $\gamma > 2.23$) implies that under semi-cooperation there is under-investment in product R&D relative to the social optimum. Since product R&D is further reduced if firms also cooperate in process R&D, social welfare declines under full cooperation relative to semi-cooperation if $\gamma > 2.23$.[14]

The above results have an interesting policy implication. When product R&D and process R&D are complementary, cooperation in one type of R&D promotes the other type of R&D if and only if it enhances incentives for the first type of R&D. Therefore, in assessing the desirability of cooperation in one type of R&D, analysis should not be confined to that type of R&D alone. The costs

[12] For example, when $\gamma = 1$, process R&D as a percentage of market size $(a - c)$ is quite large (76.2% when $s = 0.9$) whereas for $\gamma = 3$ it is quite small (only 16.8% for $s = 0.9$).

[13] Under Bertrand competition, product differentiation is not as desirable for consumers as it is under Cournot competition because prices approach marginal cost as products become more similar. In fact, simulations reveal that consumer surplus under Bertrand competition increases with s even if γ is large. As a result, semi-cooperation is less beneficial to consumers and is less likely to improve welfare under Bertrand competition than under Cournot competition.

[14] It can be shown that, given s, cooperation in process R&D lowers welfare. Thus, in addition to the above welfare loss due to reduced product R&D, full cooperation also hampers welfare by lowering process R&D.

and benefits of cooperation may spill over to the other type of R&D and such interaction should be taken into account when designing R&D policy.

5. Concluding remarks

Using a model in which increased product differentiation enhances demand, we find that product and process R&D are mutually reinforcing. As a result, firms invest more in product R&D in the presence of process R&D than in its absence. Cooperation in the two types of R&D affects R&D incentives in different ways. While cooperation in product R&D encourages both types of R&D, cooperation in process R&D has the opposite effect.

We expect our results to hold in more general settings provided that product R&D increases output (via its effect on demand). However, product R&D may sometimes result in the introduction of completely new products.[15] In these cases, product R&D by a firm may lower the demand for all existing products. If so, product R&D and process R&D may fail to be complements and product R&D decisions may be subject to a negative, rather than a positive externality. The interaction of product and process R&D under such a scenario deserves future research.

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Appendix

Proof of Proposition 3. Under Cournot competition, firm i chooses d_i to maximize $[(a-c+x^{\mathrm{C}})(2+s)]^2 - \gamma/2x^{\mathrm{C}2} - F(d_i)$. The marginal benefit of product R&D is, thus,

$$\frac{2(a-c+x^{\mathrm{C}})^2}{(2+s)^3} + \frac{2s(2-s)(a-c+x^{\mathrm{C}})}{(4-s^2)^2}\frac{\mathrm{d}x^{\mathrm{C}}}{\mathrm{d}s}, \tag{A.1}$$

which, by noting (5), is greater than that in the absence of process R&D if and only if

$$\frac{x^{\mathrm{C}2}}{(2+s)^3} + \frac{2(a-c)x^{\mathrm{C}}}{(2+s)^3} + \frac{s(2-s)(a-c+x^{\mathrm{C}})}{(4-s^2)^2}\frac{\mathrm{d}x^{\mathrm{C}}}{\mathrm{d}s} > 0. \tag{A.2}$$

[15] We are grateful to an anonymous referee for raising this point.

Since $x^{\mathrm{C}} = 4(a-c)/(\gamma H - 4)$, where $H = (2+s)^2(2-s)$, (A.2) becomes

$$x^{\mathrm{C}} + 2(a-c) + \frac{(a-c+x^{\mathrm{C}})s(2+s)}{(2-s)} \frac{(-\gamma)H'(s)}{\gamma H - 4} > 0,$$

which holds if

$$1 > \frac{s(2+s)}{(2-s)} \frac{H'(s)}{H - 4/\gamma} = \frac{s(2+s)}{(2-s)} \frac{(2+s)(2-3s)}{(2+s)^2(2-s) - 4/\gamma}. \tag{A.3}$$

Using Maple, we plotted the right-hand side of (A.3) and found that it is less than 1 when $\gamma = 8/9$. So (A.3) holds for all $\gamma \geq 8/9$. This proves the proposition for Cournot firms. The result for Bertrand case can be similarly proved. □

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