A Duopoly Model of Technological Externalities: Standards and Compatibility*

by Sanford V. Berg**

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ABSTRACT

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The existence of technological incompatibilities means that components from one system cannot be used with a basic product which is part of another system without an adaptor or (potentially costly) modifications. Demand for the basic product would be higher if all producers of the basic product adopted identical (or even "similar") technical standards. However, deviations from a firm's preferred standard will raise that firm's production costs. This paper develops a duopoly model, wherein each firm simultaneously chooses a technical standard and output level for a basic product. In this model, compatibility can promote competition. Results for rivalry are compared with the mandated second-best standards and welfare maximizing outcomes.

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1. Introduction

The links between a firm's decisions regarding technical standards and consumer valuations of incompatible products have been explored by a number of researchers. The literature presents a variety of results which are sensitive to the underlying structure of the model, including the impact of firms' choices of technical standards on compatibility, consumers' valuations for increased compatibility, costs to firms of deviating from preferred technical standards, and the underlying equilibrium concept utilized in the analysis. The essential features of the model analyzed here are listed below:

(1) Compatibility is not assumed to be an all-or-nothing outcome. Rather, there is a spectrum of standards reflecting different engineering protocols. Technical standards need not be identical--but can be "close" to one another.

Thus, in the case of computers, hardware and software standards may differ among suppliers. The adoption of vastly different technical protocols by duopolists results in a high degree of incompatibility. Note that the same supplier (as with a multiproduct monopolist) may even offer systems which are slightly incompatible--requiring adaptors or modifications in software packages (Hergert, 1987).

(2) Consumers value a particular basic product (such as an IBM PC) more if substitute products (say other microcomputers) are relatively more compatible. Thus, the "distance" between standards adopted by different suppliers determines the strength of consumer demand for the basic products.

Here, distance between standards matters--not the specific protocol standards themselves (which are transparent to the consumer). For example, compared with 20% compatibility, consumers prefer a computer that can run 80% of the software available for a computer produced by another firm.

A higher degree of compatibility means that consumers are less likely to be stranded with an unsupported technology.[1] When producers of the basic product adopt comparable technical protocols, consumers can expect a greater array of complementary products which can be attached to the basic product. Here, the positive impact of increased compatibility (closer standards) is assumed to outweigh any negative impacts from reduced product differentiation (which would have allowed firms to meet specialized needs).

(3) Due to firm-specific engineering experience and R&D programs, each firm has a different cost-minimizing technical standard. Here, the engineering protocols used by each duopolist have no effects on the quality or performance of the basic product, but affect its production costs.

We assume that the standards can be quantified and arrayed along a single dimension and that each duopolist has a different preferred technical standard. By incurring additional costs, each firm can modify its product (or production process), so the basic product utilizes standards which are closer to those chosen by its rival. The costs of deviating from its own standard could include royalty payments for utilizing proprietary features of the rival's technology. Thus, with rivalry, each duopolist chooses its technical standard independently and simultaneously: compatibility is the result of both firms' choices (Berg, 1989).

(4) Under rivalry, firms can choose their outputs and standards simultaneously and independently.

In the single stage game examined here, each duopolist takes its rival's standard and output as given when choosing its own technical standard and output level to maximize profits. An externality arises because each firm's choice of its technical standard affects not only its own demand, but also

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[1] Another example of gains to partial compatibility is in automobiles, where consumers prefer to have different manufacturers use "similar" technologies for their engines (even if specific components are not interchangeable): this reduces the degree of specialization required by mechanics--lowering repair costs. Consumers might prefer greater compatibility for other reasons: access to larger networks (independent of the likelihood the network will survive) and increases in the variety of systems that can be assembled when there is interoperability among system components.

that of its rival. This model captures the relevant calculus in settings of rapid technological change. The engineering design for the basic product and manufacturing capacity decisions are made at roughly the same time. Under rivalry, each firm is making its capacity and output choice before it knows what its rival's technical protocols will be.[2]

The model which incorporates these four features is not merely a simple variant of the network externalities characterization of compatibility problems (Katz and Shapiro, 1985). Here the mere existence of multiple (competing) standards that are perceived as "far apart" reduces the market demand for the basic product (since it has technological linkages to complementary goods). When there is substantial incompatibility, consumers conclude that the costs of complementary products will be higher than otherwise, or that additional expenditures will be required for purchasing an adaptor or "gateway" technology to achieve compatibility (David and Bunn, 1988).

Either insufficient or excessive standardization can occur in this setting. Furthermore, in contrast to other researchers, we find that compatibility can reduce equilibrium price-cost margins compared with outcomes when incompatibility occurs. Other researchers have found a different impact of compatibility on prices (Matutes and Regibeau, 1988 and Economides, 1989). Incompatibility insulates products from one another here, thereby reducing competition among rivals and leading to higher prices. Greater homogeneity between the two basic products can cause greater competition (higher output, lower prices) than when firms adopt vastly different technical standards. The model presented here retains the feature that compatibility can promote competition, while still showing how

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[2] A two-stage decision process might characterize situations of unchanging technology, where each firm observes the other's technical standards prior to making its output decision. Elsewhere, the author examines a two-stage decision-process, focusing on two situations: cooperation on selection of standards in the first stage, with output rivalry in the second, and standards leadership by one firm--so it takes the rival's reaction function into account in the first stage (Berg, 1988). In these two-stage games, a different information structure is available to each duopolist, since the choice of the rival's standard is observed prior to each firm selecting its own output. Rather than contrasting sequential decision-making with simultaneous choices of standards and output, this note focuses on an analysis of the latter.

the degree of compatibility depends on cost and demand parameters. The nature of that dependence is discussed below.

2. A Symmetric Two-Product Model

Consider two products, where the production cost for each depends on the level of output and a standard. For simplicity, we assume that standards can be characterized by a single dimension. The technical standard, T, reflects some engineering (compatibility) protocols which affect production costs, but do not have an impact on product quality. Consumers have no strict preference among standards per se. For example, the T's might represent different sets of control codes for printers, where consumers do not care which protocols are adopted--only that producers of the basic products adopt similar protocols.[3] Unlike consumers, firms have preferences over standards. Firms gain engineering experience with a localized technology--so preferred technical protocols could emerge from firm-specific R&D investments or through the adoption of production techniques which have lower costs when the output is characterized by particular engineering features. Deviations from each firm's preferred technical standard (T_i^*) raise production costs.

To characterize firms' profits formally, let $R^i(\cdot)$, $C^i(\cdot)$, and y_i denote the revenue, costs, and output of firm i. Then the profit of firm i can be written as:

$$\pi^i(y_1,y_2;T_1,T_2) = R^i(y_1,y_2;T_1,T_2) - C^i(y_i,T_i) \tag{1}$$

For simplicity, we assume there are two firms in the industry, each producing a product that is an imperfect substitute for the other (with comparable performance characteristics, such as Apple and IBM microcomputers). Firm i's total and marginal revenue fall as y_j is increased:

[3] On the other hand, increasing the number of television scan lines from 525 to 1125 per screen would yield a quality improvement: such quality-enhancing standards are not modeled here.

$$\partial R^i/\partial y_j = R^i_j < 0;\ \partial^2 R^i/\partial y_i \partial y_j < 0 \tag{2}$$

Since consumers value compatibility, demand for each product increases as the standards ($T_1 < T_2$) come closer together:

$$\partial R^1/\partial T_1 > 0;\ \partial R^1/\partial T_2 < 0\ , \tag{3a}$$

$$\partial R^2/\partial T_1 > 0;\ \partial R^2/\partial T_2 < 0\ . \tag{3b}$$

As T_1 approaches T_2, demand for *both products* increases. Furthermore, in general,

$$\partial^2 R^1/\partial y_1 \partial T_1 \gtrless 0, \tag{3c}$$

that is, although an increase in T_1 increases the level of demand, it could increase or decrease firm 1's marginal revenue. The latter occurs if demand becomes much more inelastic with increased compatibility.

On the production side, marginal production costs are positive and nondecreasing with output:

$$\partial C^i/\partial y_i > 0;\ \partial^2 C^i/\partial y_i \partial y_i \geq 0 \tag{4}$$

In addition, deviations from T_i^* raise costs:

$$\frac{\partial C^i}{\partial T_i} \begin{cases} < 0 \ for\ T_i < T_i^* \\ = 0 \ for\ T_i = T_i^* \\ > 0 \ for\ T_i > T_i^* \end{cases} \tag{5}$$

3. Mandating Standards: Welfare Maximization and Second Best Outcomes

A welfare-maximizing decision-maker can internalize the technological externality, wherein changes in T_i affect consumer valuations for product j. Welfare is defined as the difference between consumer utility (U) and production cost:

$$W(y_1, y_2, T_1, T_2) = U(y_1, y_2, T_1, T_2) - C^1(y_1, T_1) - C^2(y_2, T_2) \tag{6}$$

where $\partial U/\partial y_i > 0$ and $\partial U/\partial T_1 > 0$, $\partial U/\partial T_2 < 0$ for $T_1^* < T_1 < T_2 < T_2^*$. Consider the first order conditions for welfare maximization:

$$\partial W/\partial T_i = \partial U/\partial T_i - \partial C^i/\partial T_i = 0 \qquad i = 1, 2 \tag{7}$$

$$\partial W/\partial y_i = \partial U/\partial y_i - \partial C^i/\partial y_i = 0 \qquad i = 1, 2 \tag{8}$$

The marginal benefit from changing T_i just equals its marginal cost. Also, the marginal benefit from additional output equals marginal cost: price equals marginal cost.[4] The solution to equations (7) and (8) determines the welfare maximizing output levels and standards. The socially efficient degree of compatibility (measured by $T_2 - T_1$) takes into account both the costs of deviating from the T_i^*, and the valuations placed on the output levels of each product (recognizing the substitutability between products). For future reference, let the welfare maximizing solution be denoted as $\{y_1^W, y_2^W, T_1^W, T_2^W\}$.

As a benchmark, consider the setting wherein a government decision-maker cannot dictate output, but can mandate standards before firms choose their output levels noncooperatively.[5]

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[4] A corner solution would obtain if the goods were perfect substitutes for one another, there were fixed costs to producing each product, and the gains to compatibility were great. For simplicity, let us assume an interior solution in which both products are produced. This situation would be characterized by the own-effects of changes of y_i and of T_i exceeding the cross effects. Brander and Spencer (1983) provide a discussion of this point, in their one-stage and two-stage duopoly models of R&D and output rivalry. Here, we focus on the simultaneous selection of standards and outputs in order to underscore how this characterization of the compatibility externality sheds light on the impact of rivalry on social welfare.

[5] A highly restrictive form of such intervention would involve an agency (say, the FCC or National Bureau of Standards) mandating identical standards for both firms, achieving complete compatibility. However, in general, welfare would be greater if separate standards are set for each firm: T_1^G and T_2^G. Then the chosen degree of compatibility could balance the costs of deviating from each firm's cost-minimizing standard against the gains from expanding the demands for each product--taking into account subsequent output rivalry.

The government's problem in this setting would be to

$$\underset{y_1,\, y_2,\, T_1,\, T_2}{\text{Maximize}}\ W = U(y_1, y_2, T_1, T_2) - C^1(y_1, T_1) - C^2(y_2, T_2). \tag{9}$$

subject to:

$$y_1(T_1, T_2) = \underset{y}{\text{argmax}}\ \pi^1(y, y_2, T_1, T_2), \text{ and}$$

$$y_2(T_1, T_2) = \underset{y}{\text{argmax}}\ \pi^2(y_1, y, T_1, T_2).$$

The duopolists take their respective standards as dictated by the government, T^G_1, T^G_2, then proceed to select output levels -- with the Cournot-Nash outcome yielding marginal revenue equal to marginal cost:

$$\partial\pi^i/\partial y_i = \partial R^i/\partial y_i - \partial C^i/\partial y_i = 0\,. \tag{10}$$

Standards are set such that

$$\begin{aligned}\partial W/\partial T_i = {} & (\partial U/\partial y_i)(\partial y_i/\partial T_i) + (\partial U/\partial y_j)\,(\partial y_j/\partial T_i) + \partial U/\partial T_i \\ & - (\partial C^i/\partial y_i)(\partial y_i/\partial T_i) - \partial C^i/\partial T_i - (\partial C^j/\partial y_j)(\partial y_j/\partial T_i) = 0\ .\end{aligned} \tag{11}$$

Since $\partial U/\partial y_i = p_i$, we can combine terms and simplify (11) to obtain a Ramsey-like result:

$$(p_i - MC_i)(\partial y_i/\partial T_i) + (p_j - MC_j)(\partial y_j/\partial T_i) = \partial C^i/\partial T_i - \partial U/\partial T_i. \tag{12}$$

Because of limited control, the welfare maximizing regulator no longer equates the direct marginal benefits and marginal costs of a change in the technical standard. For example, T_1 is raised (increasing compatibility) such that direct costs are increased more than direct utility is raised. The regulator incorporates into her calculation the impact of greater compatibility on outcomes at the output rivalry stage. T_1 is increased until the sum of the equilibrium deviations of price from marginal cost for each firm (times the respective output increases attributable to the technical standard change) just equals the difference between the direct cost change and the direct change in utility: $(\partial C^i/\partial T_i - \partial U/\partial T_i)$.

To compare solutions to (6) and (9), initially impose symmetry and separable cost and demand functions:

(A1) $C^i(y_i, T_i) = A^i(T_i) + cy_i$

$\partial A^1/\partial T_1 > 0$ and $\partial A^2/\partial T_2 < 0$ for $T_1^* < T_1 < T_2 < T_2^*$,

$\partial^2 A^i/\partial T_i^2 > 0$ for $T_i > T_i^*$ and $\partial^2 A^i/\partial T_i^2 < 0$ for $T_i < T_i^*$.

(A2) $U(y_1, y_2, T_1, T_2) = u(y_1, y_2) + (y_1 + y_2)\, B(T_1, T_2)$

$p_i = \partial U/\partial y_i = u_i(y_1, y_2) + B(T_1, T_2)$

$\partial B/\partial T_1 > 0, \quad \partial^2 B/\partial T_1^2 < 0,$

$\partial B/\partial T_2 < 0, \quad \partial^2 B/\partial T_2^2 > 0$ for $T_1 < T_2$, and

$\partial^2 B/\partial T_1 \partial T_2 > 0;\ u_{12} \gtrless 0.$

In (A1), we assume increasing incremental costs of deviation from T_i^*, while allowing marginal production costs, c, to be independent of T_i. (A2) implies decreasing incremental benefits from increased compatibility ($\partial^2 B/\partial T_1^2 < 0$).

Proposition 1: Suppose (A1) and (A2) hold. Then for W = Welfare Maximization and G = Second-Best:

(1a) $T_2^G - T_1^G < T_2^W - T_1^W$ and $y_1^G + y_2^G > y_1^W + y_2^W$ } compatibility and output greater for G

or, (1b) $T_2^G - T_1^G > T_2^W - T_1^W$ and $y_1^G + y_2^G < y_1^W + y_2^W$ } compatibility and output less for G

The possibility that these two outcomes could arise is shown in the Appendix. In (1a), mandated standards are closer together and total output is greater than under welfare maximization. In (1b) the gains to forcing standards closer together are outweighed by the increasing costs of deviating from each firm's preferred standard. In either case, the Ramsey-like result in (12) holds, with welfare maximization involving compatibility different from its constrained (second best) level.

The separability of demand assumption implies that the standards levels do not affect the degree of substitutability between the basic products. Thus, consumers are assumed to perceive product-specific features as having the same importance--whether or not technical standards are closer together. If compatibility promoted substitutability, this would reinforce the Proposition 1a outcome since the constrained standards setter could use standards as an instrument to promote rivalry and increased expansion of output.

4. Cournot-Nash Rivalry

Under Cournot-Nash rivalry, output and standards are both chosen noncooperatively. Firm i takes y_j and T_j as given and maximizes profits, so in equilibrium:

$$\partial\pi^i/\partial T_i = \partial R^i/\partial T_i - \partial C^i/\partial T_i = 0 \text{ , and} \tag{14}$$

$$\partial\pi^i/\partial y_i = R^i_i(y_1,y_2;T_1,T_2) - C^i_i(y_i;T_i) = 0 \ . \tag{15}$$

Although the first order condition for output ($MR_i = MC_i$) is the same for complete rivalry and the constrained welfare maximization problem addressed in the previous section, different standards (and associated output levels) will, in general, cause marginal costs to be different. In addition, each firm ignores the revenue impact of changes in the rival's output induced by its own choice of a standard. Let the outcome be denoted as $\{y^c_1, y^c_2, T^c_1, T^c_2\}$. The following results emerge from analysis of the Cournot-Nash outcome.

Proposition 2: suppose (A1) and (A2) hold. Then

0 (2a) $T_2^c - T_1^c > T_2^W - T_1^W$ and $y_1^c + y_2^c > y_1^W + y_2^W$ } compatibility and output less for C

or, (2b) $T_2^c - T_1^c < T_2^W - T_1^W$ and $y_1^c + y_2^c > y_1^W + y_2^W$ } compatibility and output greater for C

Again, the proof is in the Appendix. Case (2a) is as expected: less compatibility and less output occur under rivalry than under welfare maximization. However, as Case (2b) illustrates, excessive rivalry is also possible: the equilibrium standards can be closer together and output greater than optimal. The explanation is straightforward. With noncooperative decision-making, the rival firms choose output and standards independent of one another. Each firm takes the standard of the other as given; the subgame perfect solution can result in each firm bringing its standard excessively near the other. When choosing their standards simultaneously, the firms do take into account how close the other firm's standard is. What is not taken into account is how a change in firm i's standard affects firm j's choice of its own standard and thus firm i's payoff. The perceived private benefits for firm 1, $\partial R^1/\partial T_1$, are equated with the private costs, $\partial C^1/\partial T_1$. However, firm 2 is lowering T_2. Excessive compatibility can arise: product demands expand, and the Cournot-Nash output exceeds the welfare maximizing output. Duopoly rents are partially dissipated due to closer standards, which yield excessive compatibility.

Comparing equations (8) and (15), we see that under welfare maximization $p_i = MC_i$, but even if $T_1^c = T_1^W$, output would be restricted under Cournot rivalry. Given cost function separability and the non-negative impact on the marginal valuation of closer standards on quantity consumed, in the (2a) situation above, the welfare maximizer will take the externality into account, bringing standards closer together. Comparing equations (7) and (14), the equilibrium condition for multiproduct welfare maximization considers marginal benefits for both products of changing T_i instead of taking into account only the marginal revenue for one product. The welfare maximizing outputs also reflect marginal benefits rather than marginal revenues. The possibility of excessive compatibility--case (2b)--arises when the standards are brought so close together that $y_1^W + y_2^W > y_1^c > y_1^W$.

As in the analyses of product quality by Spence (1975) and Sheshinski (1976), two factors tend to lead to nonoptimal quality choice (here--compatibility) by an unregulated firm with market power: (1) nonseparability of standards and quantity in the cost function, and (2) dependence of marginal valuation of, say, increased T_1 on the quantity consumed ($T_1 < T_2$). The first point reflects the potential role of production cost interdependencies. The separability assumption utilized here implies $\partial^2 C^i / \partial T_i \partial y_i = 0$, so this factor is not present here. The second point could be characterized in terms of whether output and compatibility are complements or substitutes. If quality improvements (increased compatibility) make the product demand curves steeper, the average valuation of compatibility will be greater than the valuation by the marginal consumer. The former is relevant for social optimization, but a firm with market power compares the latter with the cost of additional compatibility. Here, the assumed utility function is such that $\partial^2 U^i / \partial T_1 \partial y_1 > 0$. Contributing to inefficiency is the absence of perfect competition coupled with the technological externality.

A similar set of results arise in comparisons of complete rivalry with the second best (mandated standards) situation.

Proposition 3: Suppose (A1) and (A2) hold. Then

(3a) $T_2^c - T_1^c > T_2^G - T_1^G$

and $y_1^c + y_2^c < y_1^G - y_2^G$

or, (3b) $T_2^c - T_1^c < T_2^G - T_1^G$

and $y_1^c + y_2^c > y_1^G + y_2^G$

Case (3a) might arise if government used mandated standards as an instrument to expand output. However, when $y^c_1 > y^G_1 + y^G_2$, rival firms can again be engaging in excessive standardization relative to the mandated second best outcome (see Appendix).

5. Concluding Comments

With the evolution of high technology industries which are dependent on technical interdependencies, it is important to obtain an improved understanding of the strengths and limitations of alternative standards selection processes (see, e,g., Besen and Johnson, 1986). Interest in the topic is illustrated by the David and Greenstein (1990) survey of compatibility research: their listing of "selected" references included one-hundred and eighty items, with nearly ninety-percent appearing since 1980.[6] Many economists have examined the determinants and implications of compatibility. The purpose of this note has been to sort out the roles of various cost and demand factors, using a particular duopoly solution concept.

The model presented here is purely static and examines only the basic product--which will be part of a system, including components. Recent multiperiod analyses (Katz and Shapiro, 1986a,b) and analyses using multiple components (Matutes and Regibeau, 1988; Economides, 1989) have examined these other aspects of markets in which compatibility is important. Although these studies (and the present one) provide insights into compatibility issues, they are all somewhat limited for public policy purposes. In general, we cannot even say whether the National Bureau of Standards (or other government agencies) ought to tilt towards mandating or encouraging closer standards (and increased compatibility) or discouraging compatibility. One class of models finds reasons for the latter, as compatibility decreases rivalry. Others find that non-cooperative standardization can be inadequate--as in the excessive inertia case of Farrell and Saloner (1985) and in many of the cases of the

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[6] Gilbert's (1992) overview of a symposium on compatibility identifies additional incentive issues associated with different market structures and institutional contexts.

technological externality model presented here. In such cases, public policy which promotes compatibility can be justified. However, excessive standardization can also arise in our model. Firms deviate from their cost-minimizing standards, not taking into account standards adjustments by the rival. Such adjustments reduce the increase in marginal revenue from bringing standards closer together, dissipate profits, and reduce welfare: cost and demand parameters determine whether rivalry leads to excessive compatibility relative to what would be socially optimal. Thus, the technological externality approach sheds light on corporate behavior and industrial performance when technical standards are decision variables.

APPENDIX

Proof of Proposition 1: Second-Best Welfare Maximization

Assume the separable cost and demand functions described in (A1) and (A2). Under the symmetry assumption, $T_1^G > T_1^W$ implies $T_2^G < T_2^W$, and $T_1^G < T_1^W$ implies $T_2^G > T_2^W$. Consider the representative first order conditions:

Output

	(a)		(b)		(c)	(d)		
Second best:	$u_i(y_1^G, y_2^G)$	+	$B(T_1^G, T_2^G)$	+	$(\partial p_i/\partial y_i)$	y_i^G	$- c$	$= 0$
	(e)		(f)					
W max:	$u_i(y_1^W, y_2^W)$	+	$B(T_1^W, T_2^W)$				$- c$	$= 0$

Standards

	(g)	(h)		(i)	
Second best:	$(y_1^G + y_2^G)$	$\partial B/\partial T_1$	-	$\partial A/\partial T_1$	$= 0$
	(j)	(k)		(m)	
W Max:	$(y_1^W + y_2^W)$	$\partial B/\partial T_1$	-	$\partial A/\partial T_1$	$= 0$

The values of the terms for the equilibrium outputs and standards are shown in parentheses. Consider four possibilities regarding the relationships between outputs and standards in the two situations--second-best standards setting and welfare maximization. Given the relative values of y_1^G, y_1^W, T_1^G and T_1^W, some possible outcomes can be ruled out because they result in contradictions. In case (1), the relative sizes of $u_i(y_1^G, y_2^G)$ = (a) and $u_i(y_1^W, y_2^W)$ = (e) determine whether or not the equilibrium conditions are inconsistent--yielding a contradiction.

(1) Assume $y_1^G > y_1^W$; $T_1^G < T_1^W$; so $B(T_1^G, T_2^G) < B(T_1^W, T_2^W)$, $\partial B/\partial T_1^G > \partial B/\partial T_1^W$ and $A(T_1^G) < A(T_1^W)$, $\partial A/\partial T_1^G < \partial A/\partial T_1^W$

(a) < (e), (b) < (f), (c) < 0	{ contradiction
>	possible if (a) > (e)
(g) > (j), (h) > (k), (i) < (m)	contradiction

(2) Assume $y_1^G < y_1^W$; $T_1^G < T_1^W$

(a) > (e), (b) < (f), (c) < 0	{ possible
<	contradiction if (a) < (e)
(g) < (j), (h) > (k), (i) < (m)	possible

(3) Assume $y_1^G > y_1^W$; $T_1^G > T_1^W$

(a) < (e), (b) > (f), (c) < 0	{ possible
>	possible
(g) > (j), (h) < (k), (i) > (m)	possible

(4) Assume $y_1^G < y_1^W$; $T_1^G > T_1^W$

(a) > (e), (b) > (f), (c) < 0	{ possible
<	possible
(g) < (j), (h) < (k), (i) > (m)	contradiction

Therefore only cases (2) and (3) do not involve contradictions if (a) > (e).

Proof of Proposition 2: Welfare Maximization vs. Rivalry

Again, under the symmetry assumption $T_1^c > T_1^W$ implies $T_2^c < T_2^W$. Consider the first order conditions:

Output (a′) (b′) (c′) (d′)

Rivalry: $u_i(y_1^c, y_2^c) + B(T_1^c, T_2^c) + (\partial p_i/\partial y_i)\, y_i^c - c = 0$

(e′) (f′)

W max: $u_i(y_1^W, y_2^W) + B(T_1^W, T_2^W) - c = 0$

Standards (g′) (h′) (i′)

Rivalry: $y_1^c\ \partial B/\partial T_1 - \partial A/\partial T_1 = 0$

(j′) (k′) (m′)

W Max: $(y_1^W + y_2^W)\ \partial B/\partial T_1 - \partial A/\partial T_1 = 0$

The values of the terms are again shown in parentheses, given the equilibrium outputs and standards. Consider four possibilities.

(1) Assume $y_1^c > y_1^W$; $T_1^c < T_1^W$;

(a′) < (e′), (b′) < (f′), (c′) < 0
>

{ contradiction
possible if (a′) > (e′)

(g′) < (j′), (h′) > (k′), (i′) < (m′)
>

{ possible
contradiction if $y_1^c >> y_1^W + y_2^W$

(2) Assume $y_1^c < y_1^W$; $T_1^c < T_1^W$

(a′) > (e′), (b′) < (f′), (c′) < 0	{ possible
<	contradiction if (a′) < (e′)
(g′) < (j′), (h′) > (k′), (i′) < (m′)	possible

(3) Assume $y_1^c > y_1^W$; $T_1^c > T_1^W$

(a′) < (e′), (b′) > (f′), (c′) < 0	{ possible
>	possible
(g′) < (j′), (h′) < (k′), (i′) > (m′)	{ possible
>	contradiction if $y_1^c >> y_1^W + y_2^W$

(4) Assume $y_1^c < y_1^W$; $T_1^c > T_1^W$

(a′) > (e′), (b′) > (f′), (c′) < 0	possible
(g′) < (j′), (h′) < (k′), (i′) > (m′)	contradiction

So long as $u_1(y_1^a, y_2^a) < u_1(y_1^b, y_2^b)$ for $y_i^a > y_i^b$, we can rule out Case (1). This leaves the two cases discussed in the Section 4: inadequate and excessive compatibility.

Proof of Proposition 3: Rivalry vs. Second-Best

Under the symmetry assumption $T_1^c < T_1^G$ implies $T_2^c < T_2^G$. Consider representative first order conditions:

Output	(a″)	(b″)	(c″)	(d″)
Rivalry:	$u_i(y_1^c, y_2^c)$ +	$B(T_1^c, T_2^c)$ +	$(\partial p_i/\partial y_i)\, y_i^c$	$- c = 0$
	(e″)	(f″)	(g″)	(h″)
Second best:	$u_i(y_1^G, y_2^G)$ +	$B(T_1^G, T_2^G)$ +	$(\partial p_i/\partial y_i)\, y_i^G$	$- c = 0$

<u>Standards</u>

Rivalry: $\underset{(i'')}{y_1^c} \; \underset{(j'')}{\partial B/\partial T_1} \; - \; \underset{(k'')}{\partial A/\partial T_1} \; = \; 0$

Second best: $\underset{(m'')}{(y_1^G + y_2^G)} \; \underset{(n'')}{\partial B/\partial T_1} \; - \; \underset{(r'')}{\partial A/\partial T_1} \; = \; 0$

Consider four possibilities.

(1) Assume $y_1^c > y_1^G$; $T_1^c < T_1^G$;

$(a'') < (e''); (b'') < (f''); (c'')(d'') < 0, (g'')(h'') < 0$	possible
$(a'') > (e'')$	possible
$(i'') > (m''); (j'') > (n''); (k'') < (r'')$	possible
$>$	contradiction if $y_1^c >> y_1^G + y_2^G$

(2) Assume $y_1^c < y_1^G$; $T_1^c < T_1^G$

$(a'') > (e''); (b'') < (f''); (c'')(d'') < 0, (g'')(h'') < 0$	possible
$<$	contradiction if $(a'') < (e'')$
$(i'') < (m''); (j'') > (n''); (k'') < (r'')$	possible

(3) Assume $y_1^c > y_1^G$; $T_1^c > T_1^G$

$(a'') < (e''); (b'') > (f''); (c'')(d'') < 0, (g'')(h'') < 0$	possible
$>$	possible
$(i'') < (m''); (j'') < (n''); (k'') > (r'')$	possible
$>$	contradiction

(4) Assume $y_1^c < y_1^G$; $T_1^c > T_1^G$

$(a'') > (e''); (b'') > (f''); (c'')(d'') < 0, (g'')(h'') < 0$	possible
$<$	possible
$(i'') < (m''); (j'') < (n''); (k'') > (r'')$	contradiction

The results are interpreted in the body of the paper.

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