Tariffs, Market Structure, and the Incentive to Automate

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Abstract

We consider a simple two-stage game representing an internationally oligopolistic market. In the second stage of the game, firms purchase inputs at market prices, produce and engage in competition. In the first stage of the game, the firms may invest in altering their technology to more heavily weight capital in the production process (labor-elimination). We explore how a tariff imposed in the second stage impacts the firm's output and employment choices, given the ability to choose the technology in the first stage. We show that the protected firm responds to the tariff by increasing its adoption of labor-eliminating technologies. This reinforces the output effect of the tariff, but introduces a counteracting effect on employment. The result is robust to the mode of competition.

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1 Introduction

Over the last year the Trump administration has increased tariffs to levels not seen in the U.S. since the 1930s. The administration has floated a number of economic rationales for the use of these tariffs, many of which might charitably be described as dubious, and some of which are obviously contradictory. Nonetheless, a relatively consistent theme has been the desire to reinvigorate U.S. manufacturing and re-establish 'good' manufacturing jobs in the U.S. (see Tower et al., 2026, for an extensive discussion). The increased use of tariffs in an attempt to create domestic jobs coincides, perhaps not surprisingly, with increased concern in both the public and policy spheres over technology changes that have increased the rate of automation, whether through robots in traditional manufacturing or artificial intelligence in a wide range of tasks.

The idea that tariffs can be used to increase jobs is hardly novel, and one that most economists acknowledge, although likely with the general equilibrium caveat that the jobs created in the protected sector come at the expense of jobs elsewhere, and the second-best insight that there are more efficient policies available, following the classic reasoning of Bhagwati and Srinivasan (1969). An open question, however, is how a tariff policy might work in a world where firms have access to automating technologies and make the choice as to whether or not to adopt them and to what extent. That is the issue that we attempt to address in this paper.

The setup we use is an extension of a familiar one, the classic reciprocal dumping framework pioneered by Brander (1981) and Brander and Krugman (1983). In our version of the model, two firms are engaged in international strategic rivalry, with the problem set up as a two-stage game. In the second stage, the firms, price takers in input markets, choose an input bundle on the basis of relative factor prices in their respective markets, and compete over sales of differentiated goods in one market, with a foreign firm supplying the market via exports that may be subject to a tariff. In the first stage, firms may choose to adjust the technology that they will use for production in the second stage by making investments in automation. We show that, under certain conditions, the firm protected by a tariff makes increased investments in automating technology, which has the effect of magnifying the standard output effects of the intervention, but also has a countervailing effect on employment in the industry. It is not obvious which effect dominates, so a tariff intended to create jobs may end up destroying them as it encourages firms to automate them away. The mechanism is simple and plausible, and robust to changes in the mode of competition (as in Clarke and Collie, 2003).

The particular form of automation/technology adoption that we consider in this paper is labor-eliminating technical change. As Acemoglu and Restrepo (2018) note, a distinctive feature of automation is the use of machines to replace workers in a broad range of tasks, suggesting that a task-based framework is appropriate. Labor-eliminating technical change is a parsimonious way of capturing this feature (see Seater, 2005, Zuleta, 2008, Peretto and Seater, 2013, and Seater and

Yenokyan, 2019). We can think of it as representing automation at the extensive margin, where the range of task performed by machines expands. By contrast, modeling automation as capital-augmenting technical change (Sachs and Kotlikoff, 2012, Graetz and Michaels, 2018) corresponds to changes in the intensive margin. In this view, automation is seen as being embodied in more productive capital, which can then substitute for labor. A distinctive feature of labor-eliminating technical change is that it is subject to an adoption condition – wages must be sufficiently high relative to the price of capital in order for it to be cost-reducing.

Several papers have already explored the implications of labor-eliminating technical change in the trade context (see Pi and Zhang, 2018, Gilbert and Oladi, 2021, Gilbert et al., 2022, Gilbert et al., 2026b), so our paper is also an extension of that branch of literature. All are developed in the context of neoclassical general equilibrium models, however, rather than in the context of intra-industry trade driven by strategic considerations. Interestingly, we show that the adoption condition is not affected by the move to imperfect competition or by the market structure, although the degree of automation may be. Gilbert and Oladi (2021) note a related argument to the one presented here: a tariff may drive automation in the neoclassical context to the extent that it increases the relative wage over the adoption threshold. However, in the factor proportions framework, that would imply a tariff on labor intensive goods indirectly raising the capital-labor ratio in a capital-intensive manufactured good through factor market linkages. These linkages are not present in the current model, which instead derives the motivation for investing in automation from increases in market share. Moreover, unlike in the earlier literature, in the current framework the choice of whether and how much to automate is fully endogenous.

The remainder of the paper is organized as follows. In Section 2 we describe the model setup and derive the properties and comparative statics of the Nash equilibria of each sub-game of our model. In Section 3 we consider the comparative statics of a tariff for output and employment in the sub-game perfect Nash equilibrium. Section 4 shows that the results are qualitatively robust to the choice of mode of competition in the second stage. We end with some concluding comments, including extensions and future research possibilities.

2 Setup

We consider a two-stage game of intra-industry trade in which firms located in different countries choose the degree to which they will implement labor-eliminating technologies in the first stage, and then hire inputs, produce given the technology chosen, and compete in the second. We solve the game via backwards induction.

2.1 Stage II: Production and Competition

Let the countries be Home and Foreign, with firm H located in Home, and firm F located in Foreign. Firm F supplies the Home market only via exports. We assume markets are segmented and focus attention only on the market in the Home country. Let q_F represent production by the Foreign

firm, exclusively for sale in the Home market, and q_H represent production by the Home firm for exclusive sale in the Home market.

In the second stage of the game, firms make their input and output choices. While these choices are made simultaneously, we assume the firms are price takers in factor markets, implying that we can deal with the optimal choices in each domain independently.

2.1.1 Input Choice

Begin with the optimal choice of inputs. Assume that both firms produce their outputs using capital (K) and labor (L) with production technology described by:

$$q_H = q_H(\phi_{KH} K_H, \phi_{LH} L_H), \tag{1}$$

$$q_F = q_F(\phi_{KF} K_F, \phi_{LF} L_F). \tag{2}$$

The parameters ϕ_{KH} and ϕ_{LH}, and the Foreign equivalents, are initially normalized to unity. Changes in these parameters represent capital and labor-augmenting technological change, respectively. A rise in ϕ_{KH}, for example, lowers the capital requirement for any given level of output and labor input in the Home country. In other words, it creates an increase in effective capital in Home. We assume that the production functions are continuous, twice differentiable, increasing in both arguments at a decreasing rate, and homogeneous of degree one. That is, we assume that for the Home firm $\partial q_H/\partial K_H > 0$, $\partial q_H/\partial L_H > 0$, $\partial^2 q_H/\partial K_H^2 < 0$, $\partial^2 q_H/\partial L_H^2 < 0$, and $\alpha q_H = q_H(\alpha K_H, \alpha L_H)$, and similarly for firm F.

The firms hire their desired input bundle at given factor prices r and w. Since the production functions exhibit constant returns to scale, the marginal cost of production is constant, and by minimizing the optimal cost of producing a single unit can be described by:

$$c_H^* = c_H(r_H \phi_{KH}^{-1}, w_H \phi_{LH}^{-1}), \tag{3}$$

$$c_F^* = c_F(r_F \phi_{KF}^{-1}, w_F \phi_{LF}^{-1}). \tag{4}$$

Note how the factor augmentation parameters enter the unit cost functions inversely. The intuition is that a technical change that increases the productivity of any input by the factor x decreases the amount of that input required to produce any given output by the factor $1/x$ at any fixed usage of the remaining input. At constant factor prices, this is the same as reducing the cost of that input by the factor $1/x$ for any given output.

A change in ϕ_{KF} or ϕ_{KH} can be thought of as representing automation that occurs at the intensive margin – i.e., investment in better machines that reduces the amount of labor needed per unit of capital. Automation may also occur along the extensive margin, whereby the firms invest in implementing alternative technologies that reduce the dependence on labor directly by increasing the range of tasks that can be completed with machines. This latter form of technical change is the what we investigate here. They can be represented by what has been termed labor-eliminating

technical change, which has been defined as a decrease in the weight of labor in production and a corresponding increase in the weight of capital.

The natural of interpretation of the weight on capital is the cost-share of capital but, except in the case of Cobb-Douglas technology, that is endogenous. The output level does not affect it, because constant returns to scale ensures that each unit is produced in the same way, but it is affected by the capital-labor ratio (i.e., it varies along the isoquant even though it is constant for any isoquant along any given capital-labor ratio). Hence, we need to establish a consistent reference point. Gilbert et al. (2023) note that the cost share of capital evaluated at the unit vector is equal to the marginal product of capital per unit of output evaluated at the unit vector for *any* linearly homogeneous production function, and hence argue that the only possible way to consistently define an increase in the capital shares as the production technology changes is at the unit vector. Since we can alter the marginal products at that point (like any other) by adjusting the factor augmentation parameters, labor-eliminating technical change can be represented with an appropriate augmentation to factor productivity.

We demonstrate using the Home firm's production.[1] Consider production at the unit vector for the general production function (1). For simplicity, assume output units are normalized such that production is 1 (i.e., the unit isoquant passes through the unit vector), implying that $1 = \delta_{KH}\phi_{KH} + \delta_{LH}\phi_{LH}$, and recall the augmentation parameters are normalized to unity. The terms $\delta_{KH}\phi_{KH}$ and $\delta_{LH}\phi_{LH}$, the marginal products at the unit vector, or the capital and labor weights in production at that point (or equivalently, the associated cost shares evaluated at the implicit factor prices at the unit vector). Moreover, for any pair of augmentation parameters satisfying $0 \leq \delta_{KH}\phi_{KH} \leq 1$ and $\phi_{LH} = (1 - \delta_{KH}\phi_{KH})/\delta_{LH}$, the relationship continues to hold. Simplifying notation by recognizing that the cost shares of labor and capital sum to one, we drop the factor subscript and write $\delta_{KH} \equiv \delta_H$ from here on. We can therefore rewrite (3) in the form:

$$c_H^* = c_H\left(\frac{1}{\phi_K}r_H, \frac{1-\delta_H}{1-\delta_H\phi_{KH}}w_H\right). \tag{5}$$

When we differentiate c_H^* with respect to ϕ_{KH} (exploiting the envelope property and holding the factor prices constant). We obtain:

$$\frac{dc_H^*}{d\phi_{KH}} = \left(\frac{\delta_H}{1-\delta_H}(1-\theta_H) - \theta_H\right)\frac{c_H^*}{\phi_{KH}}, \tag{6}$$

where θ_H is the cost share of capital at the firm's current input choice. Gilbert et al. (2023) show that $d\delta_H/d\phi_{KH} = [(\bar{\sigma}_H - 1)/\bar{\sigma}_H](\delta_H/\phi_{KH})$, where $\bar{\sigma}_H$ is the elasticity of substitution between capital and labor, evaluated at the unit vector, so we can write:

$$\frac{dc_H^*}{d\delta_H} = \left(\frac{\theta_H - \delta_H}{1-\delta_H}\right)\left(\frac{\bar{\sigma}_H}{1-\bar{\sigma}_H}\right)\frac{c_H^*}{\delta_H}. \tag{7}$$

[1] A more complete analysis can be found in Gilbert et al. (2023).

From here we have the following proposition regarding labor-eliminating technical changes and optimal unit costs:

Proposition 1. *At constant factor prices, a labor-eliminating technological change will lower the unit cost of production provided that the initial capital-labor ratio is greater than unity and the sign of the elasticity of substitution minus 1 is the same at the unit vector as at the firm's initial choice.*

This proposition is stating that provided we know that the firm's current capital-labor ratio is greater than one, and that capital and labor are always either gross substitutes or gross complements in production (and this does not switch), then an increase in the cost share of capital evaluated at the unit vector will lower unit costs. Full details can be found in Gilbert et al. (2023), but the essence of the result is that a labor eliminating technical change flattens the isoquant at the point where it passes the unit vector, decreasing the cost of production above the unit vector and increasing it below. The second part of the proposition is a sufficient condition rather than a necessary one. Using the definition of the elasticity of substitution and the first order conditions for cost minimization we can show that:

$$\frac{dK_H}{K_H} - \frac{dL_H}{L_H} = \left(\frac{\sigma_H - 1}{\bar{\sigma}_H - 1}\right)\left(\frac{\bar{\sigma}_H}{1 - \delta_H}\right)\frac{d\delta_H}{\delta_H}. \tag{8}$$

Equation (8) describes changes in the capital-labor ratio with an increase in δ_H. The first bracketed term on the right is positive if capital and labor are either gross substitutes or gross complements at both the unit vector and the initial input choice. Hence, imposing the condition that the sign of $\sigma_H - 1$ does not reverse anywhere along the unit isoquant ensures that it is flatter along its entire length (i.e., for any given labor usage). We refer to the conditions under which $dc_H^*/d\delta_H$ is guaranteed to be negative (and similarly for Foreign) as the *adoption conditions*.

In Figure 1 we illustrate the relationship between the minimized unit cost and the weight of capital at the unit vector for various values of the elasticity of substitution.[2]

2.1.2 Output Choice

With each firm's optimal input choice described, now let turn to the demand side of the market. Suppose that the inverse demand functions in the Home market are:

$$p_H = p_H(q_H, q_F), \tag{9}$$

$$p_F = p_F(q_H, q_F). \tag{10}$$

[2]The figure uses production technology of the CES form introduced by Arrow et al. (1961). In this case we have $q_H = [\delta_{KH} K_H^{\rho_H} + (1 - \delta_{KH}) L_H^{\rho_H}]^{\frac{1}{\rho_H}}$, where $\rho_H < 1$ and $\rho_H \neq 0$. The parameter δ_{KH} is called the distribution parameter, and it is easily verified that it corresponds to the marginal product of capital at the unit vector. Normalizing $w_H = r_H = 1$ to simplify, the minimized unit costs in this case will be $c_H^* = [\delta_{KH}^{\sigma_H} + (1 - \delta_{KH})^{\sigma_H}]^{\frac{1}{1-\sigma_H}}$ where $\sigma_H = 1/(1 - \rho_H) > 0$ is the elasticity of substitution, and from the first order condition for cost minimization, the capital labor ratio is 1 when $\delta_{KH} = 0.5$.

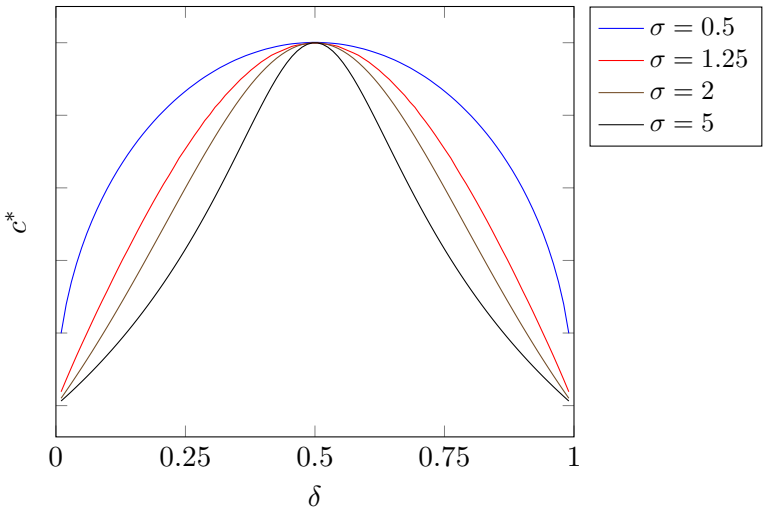


Figure 1: Optimal Unit Cost as δ Varies for Various Elasticities of Substitution

We assume that the demands are twice continuously differentiable, and are monotonically decreasing in both arguments (implying they satisfy the law of demand everywhere, and that the goods are gross substitutes everywhere). That is, we have $\partial p_H/\partial q_H < 0$ and $\partial p_H/\partial q_F < 0$, and similarly for the demand for the Foreign good. Moreover, we assume that $\partial p_H/\partial q_H < \partial p_H/\partial q_F$, and similarly for the Foreign good. That is, own price effects always dominate cross price effects.

The profits of each firm in the Home market can be written in terms of the inverse demands and optimal unit costs as:

$$\pi_H(q_H, q_F) = (p_H - c_H^*)q_H - f_H, \tag{11}$$

$$\pi_F(q_H, q_F) = (p_F - c_F^* - \tau)q_F - f_F. \tag{12}$$

where f_H and f_F reflect the cost of investing in technology changes in the first stage of the game, which are treated as sunk in the second stage. Notice that the marginal cost of supplying the Home market for the Foreign firm is $c_F^* + \tau$ because of the cost of international shipping/tariffs. We assume throughout that investment costs for both firms and transportation costs for the Foreign firm are sufficiently low that both firms are active in the Home market.

With the firms competing in quantities, differentiating each firm's profit function with respect to its own sales in the Home market yields the implicit best response functions for the second stage:

$$R_H^2(q_H, q_F) = p_H + q_H \frac{\partial p_H}{\partial q_H} - c_H^* = 0, \tag{13}$$

$$R_F^2(q_H, q_F) = p_F + q_F \frac{\partial p_F}{\partial q_F} - (c_F^* + \tau) = 0. \tag{14}$$

These expression have the usual straightforward interpretation: Each firm chooses its sales level such that the residual marginal revenue of the last unit, given sales of the rival, is equal to the minimized marginal cost of supplying that last unit (including any shipping/tariff cost for the Foreign firm).

The partial derivatives of R_H^2 and R_F^2 are:

$$R_{HH}^2 = 2\frac{\partial p_H}{\partial q_H} + q_H \frac{\partial^2 p_H}{\partial q_H^2},$$
$$R_{FF}^2 = 2\frac{\partial p_F}{\partial q_F} + q_F \frac{\partial^2 p_F}{\partial q_F^2},$$
$$R_{HF}^2 = \frac{\partial p_H}{\partial q_F} + q_H \frac{\partial^2 p_H}{\partial q_H \partial q_F},$$
$$R_{FH}^2 = \frac{\partial p_F}{\partial q_F} + q_F \frac{\partial^2 p_F}{\partial q_F \partial q_H}.$$

Assuming the second order condition for both firms is satisfied, we must have $R_{HH} < 0$ and $R_{FF} < 0$. If second-order cross price effects are assumed to be minimal, we also have $R_{HF} < 0$ and $R_{FH} < 0$ since the goods are imperfect substitutes. Totally differentiating equation (13) therefore establishes that $dq_H/dq_F = -R_{HH}^2/R_{HF}^2 < 0$ along the Home firm's best response, and similarly $dq_F/dq_H = -R_{FF}^2/R_{FH}^2 < 0$ along the Foreign firm's best response from (14). In other words, the Foreign firm decreases its sales in the Home market in response to an increase in Home firm sales, and vice versa (sales are strategic substitutes within the Home market). We denote the Nash equilibrium sales by each firm as $q_H^*(c_H^*, c_F^*, \tau)$ and $q_F^*(c_H^*, c_F^*, \tau)$.

If we assume that the production technology of the firms is symmetric, such that for the same technological choices in the first stage and same input choices, the outputs of each firm are the same, and that there is symmetry in factor prices such that $w_H = w_G$ and $r_H = r_F$, then each firm chooses the same input bundle and $c_H^* = c_F^*$. If we further assume symmetry in the demands such that for any $q_H = q_F$ we have $p_H = p_F$, implying $\partial p_H/\partial q_H = \partial p_F/\partial q_F$ and $\partial p_H/\partial q_F = \partial p_F/\partial q_H$, then since the solution of any symmetric game is symmetric, for $\tau = 0$ we must have $q_H^* = q_F^*$.

By evaluating the comparative statics around the Nash equilibrium we can obtain the following result:

Proposition 2. *Equilibrium output of each firm is decreasing in its own marginal cost and increasing in its rival's marginal cost. Output of the Home (Foreign) firm is increasing (decreasing) in the tariff.*

This is a standard result in the context of international oligopoly with competition in quantities. To see it, totally differentiate equations (13) and (14) around the Nash equilibrium quantities $q_H^*(c_H^*, c_F^*, \tau)$ and $q_F^*(c_H^*, c_F^*, \tau)$ to obtain the system:

$$\begin{bmatrix} R_{HH}^{2*} & R_{HF}^{2*} \\ R_{FH}^{2*} & R_{FF}^{2*} \end{bmatrix} \begin{bmatrix} dq_H^* \\ dq_F^* \end{bmatrix} = \begin{bmatrix} dc_H^* \\ dc_F^* + d\tau \end{bmatrix}. \tag{15}$$

Solving (15) for changes in the equilibrium quantities in terms of changes in unit costs and the tariff gives us:

$$dq_H^* = \frac{R_{FF}^{2*} dc_H^* - R_{HF}^{2*}(dc_F^* + d\tau)}{|R^2|}, \tag{16}$$

$$dq_F^* = \frac{-R_{FH}^{2*} dc_H^* + R_{HH}^{2*}(dc_F^* + d\tau)}{|R^2|}, \tag{17}$$

where $|R^2| = R_{HH}^{2*} R_{FF}^{2*} - R_{HF}^{2*} R_{FH}^{2*}$. We have established above that all terms in the coefficient matrix of (15) are negative. Since own price effects are assumed to dominate cross price effects, we have $|R^2| > 0$, and Proposition 2 is established.[3]

The results are illustrated in Figure 2. An increase in the tariff will shift the best response function for the Foreign firm downward, increasing output of the Home firm and decreasing output of the Foreign firm, for any technology choice. In Figure 2 this is shown as the movement from a to b (in blue).[4]

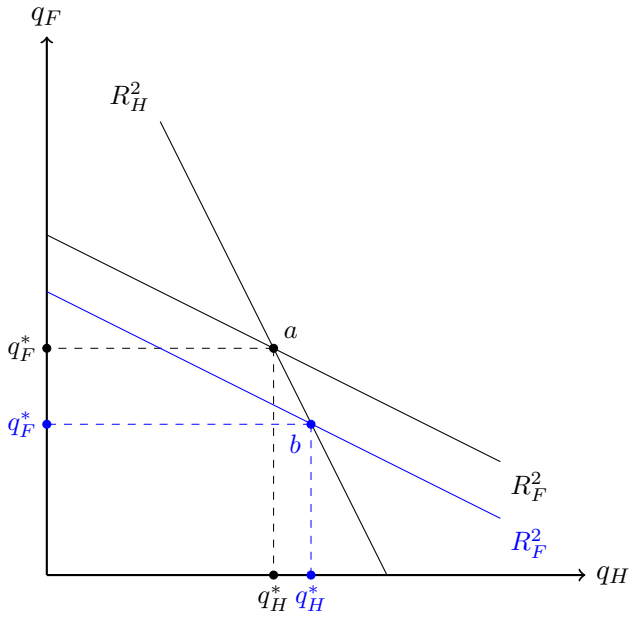


Figure 2: Equilibrium in the 2nd Stage Sub-game with Competition in Quantities

2.2 Stage I: Investment in Labor-Eliminating Technologies

In the first stage of the game, we allow the firms to choose their production technologies. More specifically, suppose that the firm's may choose the weight applied to the capital input in their respective production process, represented by the distribution parameters, δ_H and δ_F. recall that an increase in this parameter is a form of labor-eliminating technology, and can be thought of as

[3]Note that assumption ensures stability, which requires $R_{FF}^2 < R_{FH}^2$ and $R_{HH}^2 < R_{HF}^2$ in this case, see Dixit (1986).

[4]In constructing the figure we follow Dixit (1979) and Singh and Vives (1984) and assume that the utility of a representative household in Home takes the form $u = q_0 + \alpha(q_H + q_F) - [(q_H^2 + q_F^2) + 2\gamma q_F q_H]/2$, where q_0 is consumption of a numéraire good. Concavity of the function and substitutability between the Home and Foreign good implies $0 < \gamma \leq 1$. The γ parameter represents an inverse measure of the degree of product differentiation. Where $\gamma = 0$, the products are completely distinct. Setting $\gamma = 1$ is equivalent to assuming the products are homogeneous. In this case it is easy to show that the inverse demand functions are linear, as are the best response functions, and the solutions for the quantities are: $q_H^* = [(2-\gamma)\alpha - 2c_H^* + \gamma(c_F^* + \tau)]/(4-\gamma^2)$ and $q_F^* = [(2-\gamma)\alpha - 2(c_F^* + \tau) + \gamma c_H^*]/(4-\gamma^2)$.

representing automation at the extensive margin (i.e., increasing the range of production tasks that are performed by machines rather than people).

Suppose that each firm has some initial technology available that it can use with no further investments, which we denote $\bar{\delta}_H$ and $\bar{\delta}_F$. The firms can increase the range of tasks undertaken by capital relative to the baseline at a cost denoted by $f_H = f_H(\delta_H - \bar{\delta}_H)$ and $f_F = f_F(\delta_F - \bar{\delta}_F)$, respectively. We assume that $f_H' > 0$, $f_F' > 0$, $f_H'' > 0$, $f_F'' > 0$, $f_H(0) = 0$, $f_F(0) = 0$. In words, the cost of investing in new technologies that eliminate labor is increasing at an increasing rate in the degree to which the weight on capital is increased, and the cost of maintaining the status-quo is zero.

Consider the profit functions (11) and (12), evaluated at the optimal cost and output choices from the second stage, and recognizing the dependence of production costs in the second stage and investment costs in the first stage on the choice of technology. Assume that each firm independently chooses the degree of automation at the extensive margin, given the degree of automation that it believes it's rival will choose. Differentiating each firm's profit function with respect to its own technology choice yields the implicit best response functions for the first stage:

$$R_H^1(\delta_H, \delta_F) = \left(p_H^* + q_H^* \frac{\partial p_H}{\partial q_H^*} - c_H^*\right) \frac{\partial q_H^*}{\partial c_H^*} \frac{\partial c_H^*}{\partial \delta_H} + q_H^* \frac{\partial p_H}{\partial q_F^*} \frac{\partial q_F^*}{\partial c_H^*} \frac{\partial c_H^*}{\partial \delta_H} - q_H^* \frac{\partial c_H^*}{\partial \delta_H} - \frac{df_H}{d\delta_H} = 0, \tag{18}$$

$$R_F^1(\delta_H, \delta_F) = \left(p_F^* + q_F^* \frac{\partial p_F}{\partial q_F^*} - c_F^* - \tau\right) \frac{\partial q_F^*}{\partial c_F^*} \frac{\partial c_F^*}{\partial \delta_F} + q_F^* \frac{\partial p_F}{\partial q_H^*} \frac{\partial q_H^*}{\partial c_F^*} \frac{\partial c_F^*}{\partial \delta_F} - q_F^* \frac{\partial c_F^*}{\partial \delta_F} - \frac{df_F}{d\delta_F} = 0. \tag{19}$$

As usual, the interpretation is that firms increase investment in automation until the marginal increase in the firm's profits from sales resulting from the technology adjustment, conditional on the expected behavior in the second stage and the rival's technology choice, is equal to the marginal cost of making the adjustment.

Since we are evaluating the technology choices at the optimal output/input choices in the second stage, the envelope theorem implies that the first terms in (18) and (19) drop out (i.e., each firm has already optimized it's own production decision given any output decision of it's rival, it's own minimized marginal production costs, and any tariff, so equations (13) and (14) must hold at the optimum). This leaves us with only the last three terms to consider. Starting with the last term, we have the marginal investment costs necessary to alter the technology. The third terms are capturing the effect of changes in firm's own production cost, evaluated at the optimal production level. The second term is capturing effects on revenue of changes market prices as a result of changes in the rival production resulting from changes in each firm's own marginal cost of production, again evaluated at each firm's optimal output choice.

Note that $\partial p_H / \partial q_F^* < 0$ and $\partial p_F / \partial q_H^* < 0$ by the assumption that q_H and q_F are substitutes, and that $\partial q_H^* / \partial c_F^* > 0$ and $\partial q_F^* / \partial c_H^* > 0$ from Proposition 2. Hence, the first order conditions (18) and (19) can hold iff $\partial c_H^* / \partial \delta_H < 0$ and $\partial c_F^* / \partial \delta_F < 0$ for the Home and Foreign firm, respectively. That is, the adoption condition described in Proposition 1 must hold for firms to make any investments in labor-eliminating technologies. We assume from here out that it does.

The partial derivatives of R_H^1 and R_F^1 with respect to it's own and it's rival's technology choices

are:

$$R^1_{HH} = q^*_H \frac{\partial p_H}{\partial q^*_F} \frac{\partial^2 q^*_F}{\partial c^{*2}_H} \left(\frac{\partial c^*_H}{\partial \delta_H}\right)^2 + \left(\frac{\partial p_H}{\partial q^*_F} \frac{\partial q^*_F}{\partial c^*_H} - 1\right) \left(q^*_H \frac{\partial^2 c^*_H}{\partial \delta^2_H} + \frac{\partial q^*_H}{\partial c^*_H} \left(\frac{\partial c^*_H}{\partial \delta_H}\right)^2\right) - \frac{d^2 f_H}{d\delta^2_H},$$

$$R^1_{FF} = q^*_F \frac{\partial p_F}{\partial q^*_H} \frac{\partial^2 q^*_H}{\partial c^{*2}_F} \left(\frac{\partial c^*_F}{\partial \delta_F}\right)^2 + \left(\frac{\partial p_F}{\partial q^*_H} \frac{\partial q^*_H}{\partial c^*_F} - 1\right) \left(q^*_F \frac{\partial^2 c^*_F}{\partial \delta^2_F} + \frac{\partial q^*_F}{\partial c^*_F} \left(\frac{\partial c^*_F}{\partial \delta_F}\right)^2\right) - \frac{d^2 f_F}{d\delta^2_F},$$

$$R^1_{HF} = \left(\frac{\partial p_H}{\partial q^*_F} \frac{\partial q^*_F}{\partial c^*_H} - 1\right) \frac{\partial c^*_H}{\partial \delta_H} \frac{\partial q^*_H}{\partial c^*_F} \frac{\partial c^*_F}{\partial \delta_F},$$

$$R^1_{FH} = \left(\frac{\partial p_F}{\partial q^*_H} \frac{\partial q^*_H}{\partial c^*_F} - 1\right) \frac{\partial c^*_F}{\partial \delta_F} \frac{\partial q^*_F}{\partial c^*_H} \frac{\partial c^*_H}{\partial \delta_H}.$$

By virtue of the second-order condition, we must have $R^1_{HH} < 0$ and $R^1_{FF} < 0$ in order for the solutions to (18) and (19) to represent profit maxima. We assume this is the case.[5] Further, since we have established in Proposition 1 that $\partial c^*_H / \partial \delta_H < 0$ and $\partial c^*_F / \partial \delta_F < 0$ if the adoption condition holds, and in Proposition 2 that $\partial q^*_H / \partial c^*_F > 0$ and $\partial q^*_F / \partial c^*_H > 0$, and since $\partial p_H / \partial q^*_F < 0$ and $\partial p_H / \partial q^*_F < 0$ since the goods are substitutes, we further can infer that $R^1_{HF} < 0$ and $R^1_{FH} < 0$. Totally differentiating equation (18) therefore establishes that $d\delta_H / d\delta_F = -R^1_{HH} / R^1_{HF} < 0$ along the Home firm's best response, and similarly $d\delta_F / d\delta_H = -R^1_{FF} / R^1_{FH} < 0$ along the Foreign firm's best response from (19). In other words, the Foreign firm decreases its technology investments in response to an increase in Home firm technology investments, and vice versa (automation levels along the extensive margin are strategic substitutes). We denote the Nash equilibrium automation levels chosen by each firm as $\delta^*_H(\tau)$ and $\delta^*_F(\tau)$. If the firm's are symmetric, then for $\tau = 0$ we must have $\delta^*_H = \delta^*_F$. By evaluating the comparative statics around any stable equilibrium we can obtain the following result:

Proposition 3. *The degree of automation (labor elimination) of the Home (Foreign) firm is increasing (decreasing) in the tariff.*

To see establish this result, totally differentiate equations (18) and (19) around the Nash equilibrium technology choices $\delta^*_H(\tau)$ and $\delta^*_F(\tau)$ to obtain the system:

$$\begin{bmatrix} R^{1*}_{HH} & R^{1*}_{HF} \\ R^{1*}_{FH} & R^{1*}_{FF} \end{bmatrix} \begin{bmatrix} d\delta^*_H \\ d\delta^*_F \end{bmatrix} = \begin{bmatrix} -R^{1*}_{H\tau} d\tau \\ -R^{1*}_{F\tau} d\tau \end{bmatrix}, \tag{20}$$

where:

$$R^1_{H\tau} = \frac{\partial p_H}{\partial q^*_F} \frac{\partial c^*_H}{\partial \delta^*_H} \left(q^*_H \frac{\partial^2 q^*_F}{\partial c^*_H \partial \tau} + \frac{\partial q^*_F}{\partial c^*_H} \frac{\partial q^*_H}{\partial \tau}\right) - \frac{\partial c^*_H}{\partial \delta^*_H} \frac{\partial q^*_H}{\partial \tau}$$

[5] Given the signs of terms assumed and determined through Proposition 1 and Proposition 2, only the last term in (18) and (19) is unambiguously negative. The first terms are negative only if q^*_F (q^*_H) increases at at increasing rate with c^*_H (c^*_F). The second terms are potentially negative if c^*_H (c^*_F) decreases at a decreasing rate with δ_H (δ_F). In essence we need the benefits of automation to be increasing at a decreasing rate through some combination of demand/cost and investment effects.

$$R^1_{F\tau} = \frac{\partial p_F}{\partial q^*_H}\frac{\partial c^*_F}{\partial \delta^*_F}\left(q^*_F\frac{\partial^2 q^*_H}{\partial c^*_F \partial \tau} + \frac{\partial q^*_H}{\partial c^*_F}\frac{\partial q^*_F}{\partial \tau}\right) - \frac{\partial c^*_F}{\partial \delta^*_F}\frac{\partial q^*_F}{\partial \tau}$$

The only terms in these expressions that is of ambiguous sign is the second order effect, which we assume is negligible. All other terms are positive, so $R^1_{H\tau} > 0$. Similarly, $R^1_{F\tau} < 0$. Solving (20) for changes in the equilibrium automation levels in terms of changes the tariff gives us:

$$d\delta^*_H = \frac{(R^{1*}_{HF}R^{1*}_{F\tau} - R^{1*}_{FF}R^{1*}_{H\tau})d\tau}{|R^1|}, \tag{21}$$

$$d\delta^*_F = \frac{(R^{1*}_{FH}R^{1*}_{H\tau} - R^{1*}_{HH}R^{1*}_{F\tau})d\tau}{|R^1|}, \tag{22}$$

where $|R^1| = R^{1*}_{HH}R^{1*}_{FF} - R^{1*}_{HF}R^{1*}_{FH} > 0$ under the assumption of stability. It then follows that $d\delta^*_H/d\tau > 0$ and $d\delta^*_F/d\tau < 0$. The Home firm, anticipating a tariff to be applied in the second stage, will respond in the first stage by automating more (subject to the adoption condition being met), and the Foreign firm will automate less.

The analysis is illustrated in Figure 3, which depicts the best response functions and Nash equilibrium in this sub-game. From Proposition 1, we know that implementing labor-eliminating technologies is only cost reducing when the capital-labor ratio is high enough (i.e., when wages are sufficiently high relative to the rental). The critical points are $\tilde{\delta}_F$ and $\tilde{\delta}_H$. The base technologies are $\bar{\delta}_F$ and $\bar{\delta}_H$, which must lie above the critical points. The Nash equilibrium technology choice is at point a. A tariff in the second stage shifts the best response function for Home outward, and the best response for Foreign inward (in blue). The new equilibrium in the sub-game is b, with Home choosing a technology that eliminates more labor, and Foreign choosing one that eliminates less.

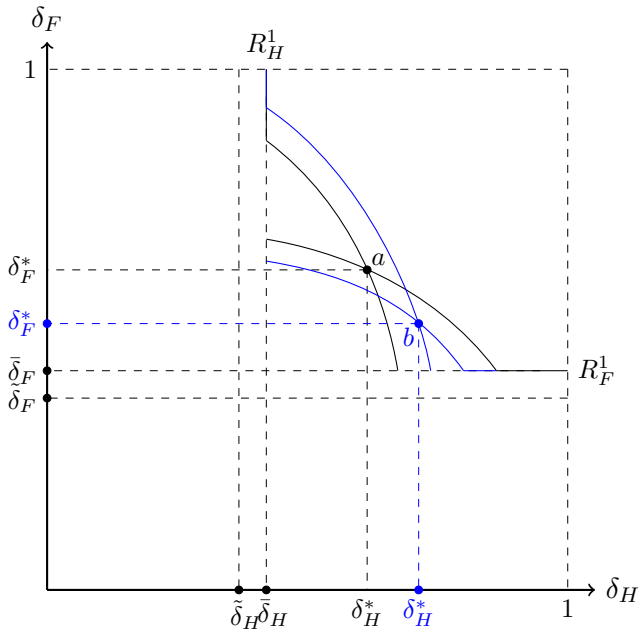


Figure 3: Equilibrium in the 1st Stage Sub-game with Competition in Quantities

The intuition behind this result is quite simple. A tariff applied in the second stage of the game will increase the market share of the Home firm at the expense of the Foreign firm, for any given production technology. This effect is stronger the more substitutable are the firm's products. An increase in market share increases the benefit of lowering marginal costs for the Home firm, for any given costs (i.e., for any given technology) of the Foreign firm, and vice versa. Hence, knowing it will have larger (smaller) share of the market in the second stage, the Home (Foreign) firm is willing to invest more (less) in technologies that eliminate labor, for any given decision of its rival, provided that labor costs relative to capital costs are sufficiently high to ensure the adoption condition is met.

3 Tariffs, Automation and Employment

A major rationale for imposing tariffs in the current environment seems to be increasing employment in the protected sector. Is the policy going to succeed in this framework? Consider the comparative statics of the output changes in the sub-game perfect Nash equilibrium, which we denote $q_H^{**}(\tau)$ and $q_F^{**}(\tau)$. It is evident that:

$$\frac{dq_H^{**}}{d\tau} = \frac{dq_H^*}{d\tau} + \frac{dq_H^*}{dc_H^*}\frac{dc_H^*}{d\delta_H}\frac{d\delta_H^*}{d\tau} + \frac{dq_H^*}{dc_F^*}\frac{dc_F^*}{d\delta_F}\frac{d\delta_F^*}{d\tau}, \tag{23}$$

$$\frac{dq_F^{**}}{d\tau} = \frac{dq_F^*}{d\tau} + \frac{dq_F^*}{dc_F^*}\frac{dc_F^*}{d\delta_F}\frac{d\delta_F^*}{d\tau} + \frac{dq_F^*}{dc_H^*}\frac{dc_H^*}{d\delta_H}\frac{d\delta_H^*}{d\tau}. \tag{24}$$

That is, the full effect of a tariff is comprised of the direct effect of the tariff on output plus the indirect of the tariff on output through its effect on costs of both firms through their technology choices. From Proposition 2, the sign of the direct effect is positive for Home in (23) and negative for Foreign in (24). Using Propositions 1, 2 and 3, the second term in (23), reflecting the effect of the tariff on Home's output choice through its own technology choice is positive, and the corresponding term is negative in (24). The third term, reflecting the effect on the Home firm of its rival's technology choice, is also positive in (23) and negative in (24). Hence:

Proposition 4. *When firms choose the degree of automation, assuming the adoption condition is met, the technology choice will reinforce the direct effect of the tariff on output.*

In other words, allowing the firms to choose their automation level will expand the standard effects of a tariff in this context, while maintaining the usual directions of change. Figure 4 illustrates. The direct effect of the tariff at constant factor prices and technology is the movement from a to b, with Foreign's best response shifted downward (blue). The indirect effect of the automation choices is the movement from b to c, with with the Home best response shifted upward and the Foreign best response shifted further downward (red).

Now consider employment. Since the technology exhibits constant returns to scale, it must be the case that total labor use in each market is equal to total output multiplied by the the optimal unit labor demand. The latter follows from the derivative properties of the unit cost function (i.e.,

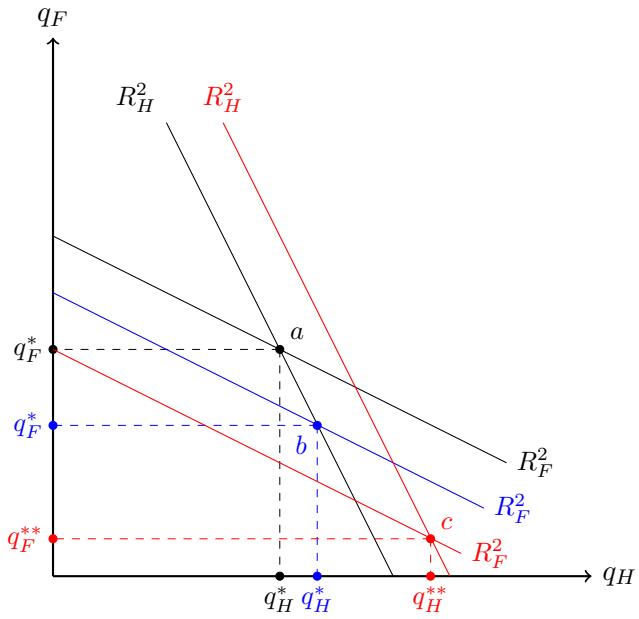


Figure 4: Effect of a Tariff in the Sub-game Perfect Equilibrium with Competition in Quantities

Shepherd's lemma). With wages held constant this means:

$$\frac{dL_H^{**}}{d\tau} = \frac{\partial c_H^*}{\partial w_H}\frac{dq_H^{**}}{d\tau} + q_H^{**}\frac{\partial^2 c_H^*}{\partial w_H \partial \delta_H}\frac{d\delta_H^*}{d\tau}, \tag{25}$$

$$\frac{dL_F^{**}}{d\tau} = \frac{\partial c_F^*}{\partial w_F}\frac{dq_F^{**}}{d\tau} + q_F^{**}\frac{\partial^2 c_F^*}{\partial w_F \partial \delta_F}\frac{d\delta_F^*}{d\tau}. \tag{26}$$

Denote the unit labor demand in Home as $a_{LH} = \partial c_H^*/\partial w_H$. Using equations (7) and (8) we have for Home:

$$\frac{da_{LH}}{d\delta_H} = -\left[\left(\frac{\bar{\sigma}_H \delta_H}{1-\delta_H}\right)\left(\frac{\sigma_H - 1}{\bar{\sigma}_H - 1}\right) - \sigma_H \frac{dc_H^*}{d\delta_H}\right]\frac{a_{LH}}{\delta_H}. \tag{27}$$

A similar expression can be derived for Foreign. Evaluating the signs of the terms in light of the results of Propositions 1, 3 and 4 we have the result:

Proposition 5. *The output effect of the tariff has a positive (negative) effect on Home (Foreign) employment, but the technology effect of the tariff has a negative (positive) effect on Home (Foreign) employment.*

The implication is that a tariff may fail to create jobs in the protected sector even while expanding output as expected, if the Home firm responds to the change in the market environment by making large enough automation investments. In general, the technology effect counteracts the output effect whenever the conditions for adoption hold. In Foreign, by contrast, the technology effect will work to mitigate the job losses arising from the loss of market share.

We illustrate what is happening in the input market of Home in Figure 5. Suppose the sub-game perfect equilibrium with no tariff results in the input choice labeled a. The minimized cost of the output is $C_H^* = c_H^* q_H^{**}$. Compared to this, a tariff, with given factor prices and technology, would

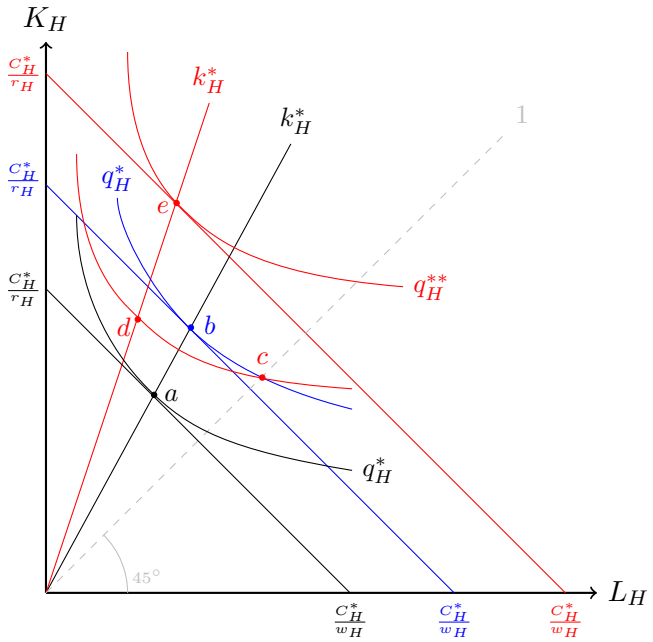


Figure 5: Effect of a Tariff in on Input Choices in the Sub-game Perfect Equilibrium

result in an increase in employment of both factors, but in the same proportions, say point b (in blue). Adopting labor-eliminating technologies stretches the isoquants around the unit vector (point c). Since the adoption conditions are met, the Home firm would choose a different technology with a tariff. The lowest cost input point for the same output as at b given the new technology choice is point d, which is tangent to the same factor price ratio as b. Because costs per unit fall, the new input choice must lie on the same factor use vector as d, somewhere to the right of d, perhaps e (red). This may or may not be to the right of the original input choice a.

4 Mode of Competition

A natural question that arises is whether and how the results obtained above are dependent on the mode of competition in the second stage. Suppose that rather than competing in quantities, the firms compete in prices in the second stage. Evidently, this change in assumptions does not affect the input choices as described in Proposition 1, but it does affect output choices described in Proposition 2. We can rewrite the demand system represented by (5) and (6) in terms of prices as $q_H = q_H(p_H, p_F)$, and $q_F = q_F(p_H, p_F)$. Since the inverse demand functions are assumed to be monotonic, it follows that $\partial q_H/\partial p_H < 0$ and $\partial q_F/\partial p_F < 0$ following the law of demand. Moreover $\partial q_H/\partial p_F > 0$ and $\partial q_F/\partial p_H > 0$ since the goods are assumed to be substitutes.[6] Differentiating the profit functions (11) and (12) with respect to each firm's own price gives us the implicit best

[6]Using the inverse function and chain rules of differentiation we can show that $\partial q_H/\partial p_F = (\partial p_H/\partial q_F)(\partial p_F/\partial q_F)/[1-(\partial p_H/\partial q_F)(\partial p_F/\partial q_H)]$. A similar expression can be obtained for $\partial q_F/\partial p_H$.

response functions with price as the strategic variable:

$$R_H^{2B}(p_H, p_F) = (p_H - c_H^*)\frac{\partial q_H}{\partial p_H} + q_H = 0, \tag{28}$$

$$R_F^{2B}(p_H, p_F) = (p_F - c_F^* - \tau)\frac{\partial q_F}{\partial p_F} + q_F = 0. \tag{29}$$

Each firm chooses its price so that marginal revenue equals the marginal production/shipping cost, given the price of the rival. The second derivatives are:

$$R_{HH}^{2B} = 2\frac{\partial q_H}{\partial p_H} + (p_H - c_H^*)\frac{\partial^2 q_H}{\partial p_H^2}$$

$$R_{HF}^{2B} = \frac{\partial q_H}{\partial p_F} + (p_H - c_H^*)\frac{\partial^2 q_H}{\partial p_H \partial p_F}$$

$$R_{FF}^{2B} = 2\frac{\partial q_F}{\partial p_F} + (p_F - c_F^* - \tau)\frac{\partial^2 q_F}{\partial p_F^2}$$

$$R_{FH}^{2B} = \frac{\partial q_F}{\partial p_H} + (p_F - c_F^* - \tau)\frac{\partial^2 q_F}{\partial p_F \partial p_H}$$

Assuming the second order conditions hold and no unusually large cross-price effects we have $R_{HH}^{2B} < 0$, $R_{FF}^{2B} < 0$, $R_{HF}^{2B} > 0$ and $R_{FH}^{2B} > 0$, implying $dp_H/dp_F > 0$ along the Home firm's best response and $dp_F/dp_H > 0$ along the Foreign firm's best response. The firm's prices are strategic complements, so the Home firm will increase it's price in response to an increase in the Foreign price, and vice versa. Let the Nash equilibrium solutions at this stage be denoted $p_H^*(c_H^*, c_F^*, \tau)$ and $p_F^*(c_H^*, c_F^*, \tau)$. As before, for symmetric demands/costs we have $p_H^* = p_F^*$ for $\tau = 0$.

$$\begin{bmatrix} R_{HH}^{2B*} & R_{HF}^{2B*} \\ R_{FH}^{2B*} & R_{FF}^{2B*} \end{bmatrix} \begin{bmatrix} dp_H^* \\ dp_F^* \end{bmatrix} = \begin{bmatrix} \frac{\partial q_H}{\partial p_H^*} dc_H^* \\ \frac{\partial q_F}{\partial p_F^*}(dc_F^* + d\tau) \end{bmatrix}. \tag{30}$$

Solving (30) for changes in the equilibrium prices in terms of changes in unit costs and the tariff gives us:

$$dp_H^* = \frac{R_{FF}^{2B*}\frac{\partial q_H}{\partial p_H^*} dc_H^* - R_{HF}^{2B*}\frac{\partial q_F}{\partial p_F^*}(dc_F^* + d\tau)}{|R^{2B}|}, \tag{31}$$

$$dp_F^* = \frac{-R_{FH}^{2B*}\frac{\partial q_H}{\partial p_H^*} dc_H^* + R_{HH}^{2B*}\frac{\partial q_F}{\partial p_F^*}(dc_F^* + d\tau)}{|R^{2B}|}, \tag{32}$$

where $|R^{2B}| = R_{HH}^{2B*}R_{FF}^{2B*} - R_{HF}^{2B*}R_{FH}^{2B*} > 0$. Hence, we have the standard results that $dp_H^*/dc_H^* > 0$, $dp_H^*/dc_F^* > 0$, $dp_H^*/d\tau > 0$, $dp_F^*/dc_F^* > 0$, $dp_F^*/dc_H^* > 0$, and $dp_F^*/d\tau > 0$. This further implies that $dq_H^*/dc_H^* < 0$, $dq_H^*/dc_F^* > 0$, $dq_H^*/d\tau > 0$, $dq_F^*/dc_F^* < 0$, $dq_F^*/dc_H^* > 0$, and $dq_F^*/d\tau < 0$.

Now consider the first stage of the game. Since the choices made at this stage take into account the optimal decisions made in the second stage, it is of no consequence whether we consider the problem in terms of optimal prices or optimal quantities from the second stage. Hence, while the

optimal quantities are different if the second stage involves quantity (for the same demand and technology, we expect prices to be higher and quantities lower when the firms compete in quantities than in prices), the structure of the first stage problem is not changed, and neither is the conclusion. Hence:

Proposition 6. *Regardless of whether competition in the second stage is in quantities or prices, the degree of automation (labor elimination) of the Home (Foreign) firm is increasing (decreasing) in the tariff.*

The reason behind this result is that despite the change in the mode of competition, the core mechanism remains intact. An anticipated tariff in the second stage increases the anticipated market share of the Home firm, increasing its incentive to invest in automation (subject to the adoption condition holding) for any level of automation undertaken by its rival, and decreases the anticipated market share of the Foreign firm, decreasing its incentive to invest in automation.

Figure 6 illustrates the best response functions and Nash equilibrium outcome.[7] An increase in the tariff shifts the Foreign best response function upward for any given technologies, shifting the Nash equilibrium of the sub-game from a to b. Both firms raise their price, with the Foreign firm raising its price by more than the Home firm. In the first stage of the game, the Home firm, anticipating a larger market share, invests more in automation, while the Foreign firm invests less. In the sub-game perfect equilibrium, the best response functions of both Home and Foreign have shifted to the left (red).

5 Concluding Comments

The economics discipline is replete with examples of the law of unintended consequences. In this paper we provide yet another example, but one that seems particularly relevant in the current trade policy environment. By encouraging firms to invest more in automation, represented here using the concept of labor-eliminating technologies, a tariff may reduce employment in an industry even as it expands output. Thus tariffs may not have their desired job-creating effect.

Gilbert and Oladi (2021) have also noted this possibility in the context of neoclassical models incorporating labor-eliminating technology shocks, but their result comes via a tariff on a labor-intensive sector increasing the relative price of labor, and (potentially) shifting the capital-labor ratio above the adoption threshold. Here wages are fixed, so there is no general equilibrium mechanism, but a rather a simple strategic one. An increase in market share increases the incentive to lower costs via automation if feasible. Since this is precisely the mechanism that drives trade itself in the reciprocal dumping context, the result is quite robust. We have made the argument without resorting to any particular demand or cost structure. It should occur in any model in which we have

[7] Again, we have used the special case of linear inverse demands from Singh and Vives (1984) to construct this figure. It is straightforward to show that in this special case we have linear best response functions with solutions $p_H^* = [(2-\gamma-\gamma^2)\alpha+2c_H^*+\gamma(c_F^*+\tau)]/(4-\gamma^2)$ and $p_F^* = [(2-\gamma-\gamma^2)\alpha+2(c_F^*+\tau)+\gamma c_H^*]/(4-\gamma^2)$. The corresponding quantities will be $q_H^* = [(2-\gamma-\gamma^2)\alpha-(2-\gamma^2)c_H^*+\gamma(c_F^*+\tau)]/(4-\gamma^2)(1-\gamma^2)$ and $q_F^* = [(2-\gamma-\gamma^2)\alpha-(2-\gamma^2)(c_F^*+\tau)+\gamma c_H^*]/(4-\gamma^2)(1-\gamma^2)$.

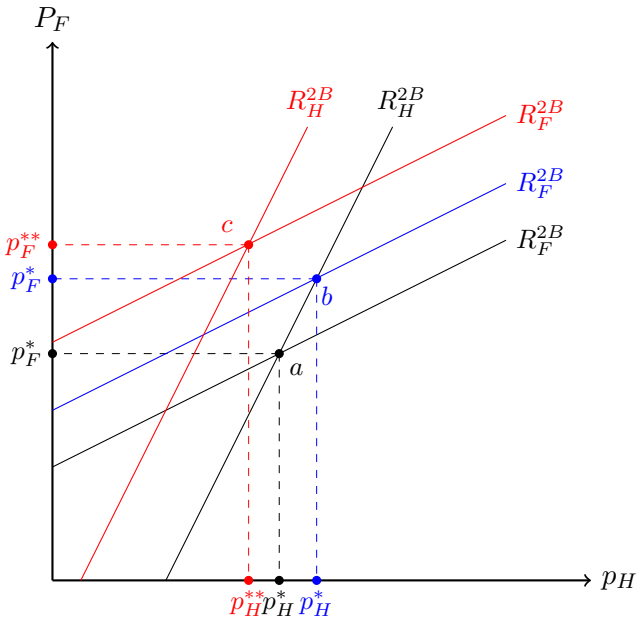


Figure 6: Effect of a Tariff in the Sub-game Perfect Equilibrium with Competition in Prices

segmented markets and the policy results in an increase in perceived marginal revenue. We have demonstrated in the paper that the result holds under both Cournot and Bertrand competition. Moreover, unlike in Gilbert and Oladi (2021) and related papers, where firms only consider whether or not to adopt a given new technology, here the technology choice is fully endogenous. Interestingly, the market structure does not alter the basic threshold conditions for adoption, although it does of course alter the profitability of doing so, and therefore the extent to which it occurs.

While the focus of this paper has been on labor-eliminating technologies, which represent automation along the extensive margin, the core results are also robust to changes in technology along the intensive margin (i.e., capital-augmenting technological change, better machines). In this case the same technology, output and employment effects would arise, but since capital-augmenting technical change is always cost reducing, there is no adoption condition. Labor-augmenting technologies would work similarly with respect to output, but the direction of the employment effect would be dependent on the elasticity of substitution. Investments generating neutral technology changes would leave the capital-labor ratio unchanged and therefore employment effects would have to coincide with output effects. Of course, the fact that neutral technology change does not result in an increase in the use of capital relative to labor is precisely what makes it unrealistic in the context of automation.

There are some remaining questions. While the mechanism is robust, it would be useful to investigate further how the magnitudes vary with aspects of the market structure. It would also be useful to consider other potential policy instruments. Generally, if the objective is to increase employment in a particular sector, the most efficient policy would be a wage subsidy to that sector. If such a subsidy pushed the effective wage low enough to push the capital-labor ratio at the initial

technology below the adoption threshold this would be a plausible solution. The output effects would be similar to a tariff in the standard models. Smaller wage subsidies would, however, have a similar effect to tariffs in terms of encouraging automation. A tax on investments in automation would be necessary to choke off that mechanism. All these policies have welfare implications that should be considered.

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