June 2022

Working Paper

How innovation affects labor markets: An impact assessment

Anton Korinek

This working paper is available online at: https://www.brookings.edu/center/center-on-regulation-and-markets/

Center on Regulation and Markets at BROOKINGS

Disclosure

The Brookings Institution is financed through the support of a diverse array of foundations, corporations, governments, individuals, as well as an endowment. A list of donors can be found in our annual reports published online here. The findings, interpretations, and conclusions in this report are solely those of its author(s) and are not influenced by any donation.

How innovation affects labor markets: An impact assessment

Anton Korinek*

June 2022

Abstract

I develop an economic framework to evaluate the impact of a technological innovation on labor demand and inequality, decomposing the effects into five channels that are quantified using data that corporations routinely collect in their accounting and financial planning and analysis departments: (i) the direct channel captures how the innovation changes factor inputs for given output; (ii) the demand channel reflects how pricing decisions affect product demand; and (iii) the factor reallocation effect captures how redundant factors are redeployed in the economy. When supply chain effects matter, (iv) the vertical channel traces the effects on factor demand along a firm's value chain. Moreover, when there are significant within-industry demand effects, (v) the horizontal channel analyzes how factor demand among competitors and providers of complements is affected. The framework informs companies, policymakers, and civil society about what types of innovations and policy environments are desirable to deliver shared prosperity. I also provide a sample application of how an automation tool introduced in the fast food industry would generate a redistribution from unskilled to skilled workers.

Keywords: technological progress, AI, inequality, impact assessment
JEL Codes: E64, D63, O3

*Brookings, Economic Studies and Center on Regulation and Markets; University of Virginia, Department of Economics and Darden School of Business; Partnership on AI, Shared Prosperity Initiative; NBER; CEPR; and Centre for the Governance of AI. I would like to thank Sharon Korinek for advice on accounting and FP&A and Katya Klinova, Susan Lund and Simi Rujiwattanapong as well as participants in a Brookings AI Authors Conference and seminars at CEU, PUC Rio, Sao Paolo, and UAB for helpful comments, and Donghyun Suh for excellent research assistance. All remaining errors are my own. I gratefully acknowledge financial support from Brookings, the Bankard Fund for Political Economy at UVA, the Center for Innovation, Growth and Society (CIGS) at INET, and the Partnership on AI's Shared Prosperity Initiative.

1 Introduction

Recent advances in artificial intelligence (AI) and related emerging technologies (ET) have led to widespread concerns about job displacement and increases in inequality. In prior decades, there was a widely-held belief among economists that technological progress will ultimately lift all boats. However, the experience of the most recent decades has led to a rethinking and a recognition that workers may in fact be made worse off by some technological advances (see e.g., Acemoglu and Restrepo, 2018; Berg et al., 2018; Korinek and Stiglitz, 2019). This raises the question of how to distinguish innovations that would benefit workers by increasing their marginal products versus innovations that would reduce the competitive market wages of workers. The question is complicated by the fact that a significant part of the effects of an innovation depends on general equilibrium effects that are not immediately obvious to innovators who develop a new technology.

I develop an economic framework to evaluate the impact of technological advances on the equilibrium demand for different types of labor, and to analyze how these effects depend on both the pricing strategies of innovators and the institutional structure of the economy, including its market structure and intellectual property regime. The labor market effects of an innovation are decomposed into five distinct channels: a direct channel, a demand channel, vertical effects along the firm's value chain, horizontal effects among competitors and providers of complements, and a factor reallocation effect that captures how redundant resources are redeployed in the economy. The objective of the framework is to help to inform companies, policymakers, and civil society about what types of AI/ET innovations are desirable from the perspective of avoiding excessive worker displacement and to contribute to economic growth with shared prosperity rather than growing inequality.

The framework distinguishes the effects of a technological innovation on factor demand and by extension on inequality into the following channels:

1. The **direct effects** capture how an innovation changes an organization's factor demand for a given level of output. It reflects that under a new technology, the composition of factor inputs may change. For example, the organization may need less labor input or more energy input to produce the same amount of output. In general, an innovation implies that the same amount (or the same quality-adjusted amount) of output can be produced with fewer inputs,

thereby increasing efficiency. When an innovation reduces the amount of a factor that is demanded, it is frequently labeled a "displacement" effect. Keeping track of this direct effect is important because it reflects the most tangible impact of an innovation without relying on economic modeling assumptions – it is therefore most immediately accessible to innovators. However, it is definitely not a full guide to the labor market effects of a given innovation.

2. The **demand effects** of an innovation reflect that an innovation generally triggers an increase in demand, either because it leads the innovating organization to lower its prices or because it leads to better products (i.e., lower prices per efficiency unit of product). The demand effect depends crucially on the firm's pricing strategy, which is in turn influenced by the competitive landscape in which the organization is operating, its market power, and the prevailing intellectual property (see e.g., Furman and Seamans, 2019).

3. The **factor reallocation** effect captures what happens as the economy re-equilibrates to clear factor markets after all of the other described effects have taken place. It reflects that innovation-induced changes in factor demand necessitate changes in factor prices. For example, when one type of labor is made redundant by an innovation, wages for type of labor need to decline so it can be reallocated to other sectors of the economy in the short- to medium term. Likewise, increases in factor demand are met by reallocating the factors from elsewhere in the economy and correspondingly reducing output in the sectors from which the factors are drawn.[1] For example, if one organization hires more AI engineers, then in the short term, they are drawn from other sectors in the economy, reducing output there.

These three channels capture the full effects of a technological innovation that is contained to a given sector in general equilibrium. In some applications, it is furthermore desirable to break out two additional channels that are relevant in specific circumstances and that we analyze in two extensions.

4. The **vertical effects** of an innovation include how changes in an organization's demand for inputs feed through the organization's supply chain and in

[1] For factors that are in variable supply, including elastic labor, demand changes will also result in a supply response, e.g., some of the workers who are in less demand will reduce hours worked or will drop out of the labor market altogether.

turn lead to changes in factor demand among the organization's suppliers. For example, if the new technology requires fewer inputs of a labor-intensive intermediate input, then it will lead to less labor demand among the organization's suppliers. These effects can be captured in an "all-in" factor demand function of the organization.

5. **Horizontal effects** capture that an innovation and the resulting demand effects at one organization will also affect the producers of competing products that are substitutes as well as the producers of complementary products. Typically, an innovation at one organization will shift demand away from competitors to the innovating organization as consumers move their demand there to take advantage of lower prices or higher-quality products. This means that competitors typically reduce their all-in factor demands.[2] Moreover, the increase in demand for the products of the innovating firm also frequently leads to an increase in the market for complements, e.g., accessories or services for the products, who will therefore expand their all-in factor demand.

Together, these channels account for the full general equilibrium impact of a technological innovation for given factor supplies.

As a sample application of the described framework, I consider a fast-food chain that employs an AI-assisted robot technology that replaces 10% of the unskilled workforce but requires additional skilled engineers to operate the technology. Working through all five channels described above, I find that the technology would reduce the wage bill of unskilled workers by more than $200m while increasing the wage bill of skilled workers by more than $100m.

In the longer term, the effects analyzed so far may be complemented by a factor accumulation (or factor deepening). This effect may capture that in the longer term, changes in factor demand may affect the accumulation of those factors that can be accumulated, such as physical or human capital. For example, greater demand for capital will lead to what is called "capital deepening" – an increase in the amount of capital per capita that is accumulated. Similarly, changes in

[2] For example, Acemoglu et al. (2020) and Koch et al. (2021) document that the adoption of industrial robots led to increases in employment at adopting firms but decreases in employment at competing firms, suggesting that the latter are losing business to the innovating firms that adopted robots.

the demand for human capital will lead to the accumulation or decumulation of specific types of human capital. These factor accumulation responses may over time undo some of the adverse effects of technological innovations on specific factor earnings.

An additional interesting question is how a given innovation today will affect the future path of innovation. There are competing effects at work. On the one hand, a "stand on the shoulders of giants" effect captures that an innovation allows for future follow-up innovations that build on it. On the other hand, the "fishing out the pool" effect captures that whenever one innovation is developed to solve one problem, the next problem will be more difficult to solve. Moreover, these effects are largely external to the organization under consideration, implying that they represent externalities. These questions are of a more technological nature and are beyond the scope of the given economic framework.

An observation about the role of uncertainty in the described framework: The effects of an innovation are rarely foreseeable with certainty since innovation is inherently about something novel. In an ex-post evaluation of the impact of an innovation, this does not matter. But if the framework is used to evaluate the future effects of an innovation, there will always be uncertainty about the described effects. Depending on the application, it is important to properly take this uncertainty into account. For example, if the framework is employed with an eye towards ensuring that an organization's innovations do not hurt workers, a risk-averse social welfare function that weighs potential losses for workers more heavily than potential gains would be appropriate.

Literature There are three strands of economic literature that are closely related to the topic of this paper.

One of these strands provides a rich positive analysis of the effects of technology on labor and goes back all the way to Keynes (1930). More recent prominent examples include Autor (2015, 2019), Bessen (2016), Acemoglu and Restrepo (2018, 2021), Autor and Salomons (2018), Acemoglu et al. (2020), among others, who focus on documenting the effects of past technological changes at the sectoral or economy-wide level. Our contribution is to lay out a framework that allows us to evaluate the macroeconomic effects of one specific technological innovation.

A second strand of literature provides predictions for how artificial intelligence and related technologies will affect labor demand in the future, focusing on how easy to replace different jobs in the economy are. Examples include Frey and Osborne (2013, 2017), Manyika et al. (2017), Brynjolfsson et al. (2018), Lund et al. (2019) or, with a more futuristic focus, Bostrom (2014), Tegmark (2017) or Korinek and Juelfs (2022).

A third strand of literature calls for efforts to steer technological advances to be more labor-friendly, for example Costinot and Werning (2018), Acemoglu and Restrepo (2019), Klinova (2022) and Korinek and Stiglitz (2021b); this paper complements their calls with a careful analysis of how to do so. The contribution of this paper is to provide a tangible framework that innovators can employ to evaluate the implications of specific technological innovations on factor demand and that relies on data that corporations routinely collect in their accounting and financial planning and analysis departments. Moreover, the framework does not impose parametric restrictions on innovators' production technologies and is therefore flexible enough to account for the wide range of production technologies that companies and other organizations may employ.

2 General Model

2.1 Environment

Consider an economy with a representative agent who is endowed with $h = 1, ..., H$ factors of production $L = (L_1, \ldots, L_H)$ that are in fixed supply. These factors include the traditional factors labor and capital but may be differentiated into as many subcategories as is useful for the impact analysis performed. For example, it will frequently be useful to distinguish different segments of the labor market, differentiated e.g., by skill level, skill category, or geographical location. What matters is that each defines a separate market segment of factors that are imperfectly substitutable. When useful, capital may be differentiated into reproducible capital like machines, or into land, natural resources, energy, etc. Additionally, it will frequently prove useful to include a fixed factor E to which any profits accrue, as these play an important role in the distributive analysis that we conduct.

Aggregate Production Technology The agent derives utility from a final good, which is an aggregate of $j = 1, \ldots J$ differentiated intermediate goods $(C_1, \ldots, C_J)$

that are combined using a production function

$$C = G\left(C_1, \ldots, C_J\right) \tag{1}$$

which is increasing in each element and quasi-concave and satisfies constant returns to scale.

Example 1 (CES Aggregator)**.** A commonly used production function that satisfies the assumption is a CES aggregator with elasticity of substitution σ

$$C = \left[\sum_j a_j C_j^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \text{ for } \sigma \neq 1 \text{ or } C = \prod_j C_j^{a_j} \text{ for } \sigma = 1 \tag{2}$$

where the weights a_j determine the importance of good j in final output and satisfy $\sum_j a_j = 1.$

Intermediate Goods Technologies An intermediate good j is produced by employing a vector of factor inputs $\ell_j = \left(\ell_{j1}, \ldots, \ell_{jH}\right) \geq 0$ in a production function $F_j\left(\ell_j, A_j\right)$, which is quasiconcave in ℓ_j, and where A_j reflects technological characteristics. This production function is indexed by j since it will generally differ across different intermediate goods. A simple example is a Cobb Douglas function, $F^j\left(\ell_j, A_j\right) = A_j \ell_{j1}^{\alpha_{j1}} \cdots \ell_{jH}^{\alpha_{jH}}$, which combines production factors with different weights $\alpha_{jh} \geq 0$ at overall productivity A_j. Another example is a production function requiring fixed cost $\bar{\ell}_j$ before output can be produced using a function $\tilde{F}^j\left(\ell_j - \bar{\ell}_j; A_j\right)$ so that $F^j = \left\{0 \text{ if } \ell_j < \bar{\ell}_j; \tilde{F}^j\left(\ell_j - \bar{\ell}_j; A_j\right) \text{ if } \ell_j \geq \bar{\ell}_j\right\}$. Below in Section 4, we also consider an extension that allows for inputs of other intermediate goods and therefore allows us to capture production networks.

Discussion The model structure is intentionally kept simple to focus the analysis on how technology affects factor demands. Although we do not do so in the present article, there are several dimensions in which the framework could be extended and that may be relevant in certain situations. First, assuming constant returns for the final goods aggregator and a representative consumer implies that there is a single consumption basket and that the demand for intermediate goods is independent of the level of income and of who receives the income in the economy. This may be a useful first approximation, but it is well known that consumption baskets differ by income levels and geographical location. By implication, redistributions of factor income may give rise to changes in the relative demand for intermediate goods. Second, endogenizing the factor supplies, which are currently exogenous, would introduce another dimension of adjustment that could mitigate the price effects of changes in factor demand. Whereas labor supply is relatively inelastic, this matters a lot for factors that are supplied relatively elastically.

2.2 Market Structure

Taking final goods as the numeraire, denote by $w = (w_1, \ldots, w_H)$ the vector of factor prices at which the factors of production $L = (L_1, \ldots, L_H)$ trade, and by $(P_1, \ldots, P_J)$ the vector of goods prices at which the intermediate goods $(C_1, \ldots, C_J)$ trade in the market. The representative consumer supplies all her factor endowment, earning factor income $I = w \cdot L$, and chooses a consumption bundle of intermediate goods $C = (C_1, \ldots, C_J)$ by solving

$$\max_C G\left(C_1, \ldots, C_J\right) \quad \text{s.t.} \quad P \cdot C \leq I$$

which can be solved for the Marshallian demand functions

$$C_j = D_j\left(P; I\right) \tag{3}$$

In the CES example above, the demand function for good i is $D^j\left(P_j; I\right) = a_j^\sigma I / P_j^\sigma$.

Intermediate goods producers We consider several scenarios for intermediate goods producers and do not restrict our analysis to a specific setting among these:

A representative competitive firm i in sector j takes both the goods price P_j and factor prices w as given. Denoting by A_j the technology parameters of the firm, it solves

$$\max_{\ell_i} P_j F^j\left(\ell_i; A_i\right) - w \cdot \ell_i \tag{4}$$

where the inner product $w \cdot \ell_i = \sum_h w_h \ell_{ih}$ reflects the total factor expenditure. The vector of factor bills $b_i = (b_{i1}, \ldots, b_{iH})$ is given by the element-by-element product

$b_i = w \circ \ell_i = (w_1 \ell_{i1}, \ldots, w_H \ell_{iH})$ and reflects the total amount that the representative firm spends on each factor h.

The dual to this problem is the representative firm i's cost minimization problem, which defines an H-dimensional factor input demand function to produce output level Y_i for given factor prices and technology,

$$L^i \left(Y_i, w; A_i\right) = \arg\min_{\ell_i} w \cdot \ell_i \quad \text{s.t.} \quad F^j \left(\ell_i; A_i\right) \geq Y_i \tag{5}$$

Using the partial derivative $L_Y = \partial L_i / \partial Y_i$ of this function, the solution to the firm's profit maximization problem can be written as

$$P_i = w \cdot L^i_Y \left(\cdot\right) \tag{6}$$

A monopolistic firm i in sector j under CES final demand takes factor prices as given but internalizes the consumer's demand function for intermediate good j. The consumer's optimization problem when the aggregator function $G\left(\cdot\right)$ takes the CES form (2) with elasticity $\sigma > 1$ gives rise to the demand and inverse demand functions

$$C^j \left(P_i; I\right) = \left(\frac{a_i}{P_i}\right)^{\sigma} \cdot I \qquad P^j \left(C_i; I\right) = a_i \left(\frac{I}{C_i}\right)^{\frac{1}{\sigma}}$$

The monopolistic firm i with technology A_i solves

$$\max_{Y_i} P^j \left(Y_i; I\right) Y_i - w \cdot L^i \left(Y_i, w; A_i\right) \tag{7}$$

which gives rise to the optimality condition

$$\left(1 - \frac{1}{\sigma}\right) P_j = w \cdot L^i_Y \left(\cdot\right) \tag{8}$$

Compared to a competitive firm's optimality condition (6), a monopolistic firm charges a markup of $\frac{1}{\sigma - 1}$ over its marginal cost and earns profits $\pi_i = \frac{1}{\sigma} P_j Y_i$.

Observe that the behavior of the described monopolistic firm is isomorphic to that of a representative competitive firm i that combines output from production function $F^j \left(\ell_i; A_i\right)$ with a fixed factor $E_j \equiv 1$ in a Cobb-Douglas aggregator with shares $\frac{\sigma-1}{\sigma}$ and $\frac{1}{\sigma}$. Defined this way, the fixed factor E_j earns a competitive factor rent $w_{Ej} = \pi_i$ equaling the profits earned by the monopolistic firm.

In the following, we will assume w.l.o.g. that there is a representative competitive firm in each sector j, and that we label any firm profits as factor returns on the fixed factor E_j in the described manner to simplify notation.

2.3 Equilibrium

Definition 1 (Equilibrium)**.** The equilibrium of the described economy consists of a collection of factor and goods prices (w, P) as well as factor allocations and intermediate goods production levels $\{\ell_i\}$ and $\{Y_i\}$ as well as final goods consumption C that satisfy the maximization problems of the representative consumer and of the representative firm in each sector, and that clear factor and goods markets, $\sum_i \ell_i = L$ and $C_i = Y_i \forall i$.

Since there are no market imperfections in the representative intermediate goods producer version of the model, the first welfare theorem holds and we can equivalently consider the competitive equilibrium or the planner's allocation. For our analysis below, it will be helpful to define the aggregate production function when factors are optimally allocated to intermediate goods producers as

$$F(L) = \max G\left(\{F^j(\ell_j; A_j)\}_j\right) \quad \text{s.t.} \quad \sum_j \ell_j \leq L \tag{9}$$

This function represents the maximum amount of final good that can be produced for given factor inputs L and prevailing technology levels $\{A_j\}$.

3 Effects of Technological Change

At the center of this paper's analysis is to assess the impact of a technological change at a firm i on factor demand and earnings. For simplicity of notation, we assume in this section that firm i is the representative firm in intermediate goods sector i. This analysis is useful to introduce the described framework and sufficient to describe either innovations by firms that are the sole producer in a sector or innovations that affect all firms in a given sector. We will extend our analysis to alternative sectoral structures in Section 5.

Assume an economy that is in equilibrium as defined above, and consider the effects of a technological change at firm i on the economy. In the following, I will trace these effects step-by-step in a manner that builds on the data that is typically available in the accounting and financial planning and analysis departments in a corporate setting. For each step, I will first analyze the implications of a marginal technological change dA_i within our theoretical model. Building on this, I will analyze how to measure the effects of technological change in practice, taking into account that technological changes are discrete so that the findings of the theoretical model apply to a first-order approximation. Appendix 7 complements this analysis by providing an analytic example of an economy with Cobb-Douglas final goods production and constant-returns intermediate goods production function, in which the described effects can be solved for explicitly.

3.1 Direct Effect

Denote by the direct (or partial-equilibrium) effect of an innovation how it affects firm i's factor demand and factor bill, profits, and productivity, taking as given all goods and factor prices in the economy. Since all goods prices are unchanged, demand for the firm's output is also unchanged at Y_i. For clarity of notation, I use Roman numerals to label the different steps of our procedure, with the direct effect carrying the superscript Roman I. Accordingly, I denote the direct effect on factor demands by

$$d\ell_i^I = L_A^i \left(Y_i; w, A_i\right) dA_i \tag{10}$$

where we use the notation $L_A^i = \partial L^i \left(\cdot\right) / \partial A_i$ for the respective partial derivatives. The direct effect on the factor bill of firm i (excluding effects on the fixed factor capturing profits) is

$$db_i^I = w \cdot d\ell_i^I$$

An innovation is desirable for firm i if it reduces its factor bill, so in most situations we would find $db_i^I < 0$. (In some cases, the cost savings may only kick in once demand for good i has expanded sufficiently.) This captures that the innovation allows the firm to produce its output with fewer inputs, although demand for some factors may go up as long as the additional cost is offset by savings on other factors. For example, automation may increase demand for capital at the expense of labor, or demand for AI engineers at the expense of unskilled workers. The direct effect on the firm's profits is $d\pi_i^I = -db_i^I$ which is generally positive. In other words, there is a redistribution from regular factor income to profits in the amount of db_i^I. The direct effect on the firm's total factor productivity growth is $-db_i^I/b_i$, which captures by what percentage the firm becomes more efficient in converting factor inputs into output.

Discussion Capturing the direct effects of an innovation is useful for an impact assessment since it provides a picture of the most immediate changes that an innovation may result in. If consumer demand and factor markets take time to adjust to the innovation, it may also describe the economy's allocation in the very short run: there is a redistribution from factor earnings to profits, and there are unemployed factors. However, since the direct effects describe partial equilibrium effects, it goes without saying that the resulting allocation would not be an equilibrium, and equilibrating effects will arise that push the economy in the directions discussed below.

Measurement The direct effect of an innovation is easy to measure as the change in factor inputs of firm i for given output Y_i. This data is readily available to a firm conducting an impact assessment. The direct effects on labor demand and the factor bill are given by $\Delta\ell_i^I$ as well as $\Delta b_i^I = w \cdot \Delta\ell_i^I < 0$ and $\Delta\pi_i^I = -\Delta b_i^I > 0$. A first-order approximation of the direct effect on firm i's total factor productivity growth is $-\Delta b_i^I/b_i > 0$.

3.2 Demand Effect

The demand effect of the innovation captures how much the effective demand for intermediate good i changes in response to firm i's price changes in a partial equilibrium in which factor prices and consumer income are still taken as given. For the following analysis, assume that we can translate any quality improvements due to an innovation into increases in efficiency units of the intermediate good produced so we do not need to separately keep track of quality effects. We consider how price changes of good i depend on the magnitude of the direct effect as well as on the demand elasticity for intermediate good i. We use the superscript Roman II to denote changes associated with demand effects. In Section 5 below, we analyze how to account for richer market structures.

In our theoretical model, prices are determined by market forces (for competitive firms) or by optimal pricing decisions (in the case of monopolistically competitive firms). For both a representative competitive firm i, as described in problem (4), and for a monopolistically competitive firm i, described in problem (7), the market price P_i therefore falls in proportion to the decline in factor bill, $dP_i^{II}/P_i = db_i^I/b_i$, or equivalently

$$d\log P_i^{II} = d\log b_i^I$$

For given income, the resulting effect on the change in demand C_i of good i is given by

$$d\log C_i^{II} = \epsilon_i d\log P_i^{II}$$

where the demand elasticity $\epsilon_i = \partial D^i/\partial P_i \cdot P_i/D^i$ of intermediate good i derives from the demand function (3). In the case of the CES aggregator for intermediate goods (2), the demand elasticity is simply $\epsilon_i = \sigma$.

The change in demand for good i entails an increase in firm i's factor input demand of

$$d\ell_i^{II} = L_Y^i\left(Y_i; w, A_i\right) dC_i^{II}$$

which is additive to the direct effect $d\ell_i^I$, as well as an associated increase in the firm's factor bill $db_i^{II} = w \cdot d\ell_i^{II}$ which is additive to db_i^I. Moreover, profits decline in response to a lower price but may increase because of the expansion in demand.

Discussion For firms, an important aspect of our technological impact assessment is that their pricing strategies play a crucial role in delivering broadly shared increases in prosperity. At one extreme, if a firm leaves prices unchanged after engaging in a cost-saving innovation, demand effects are zero – the firm increases its profits but will not deliver greater prosperity to other factor owners. By contrast, in a perfectly competitive market, prices are competed down in parallel with any cost reductions, and firm output expands and induces more efficient firms to increase their factor demand.

For policymakers, this emphasizes the importance of competition in ensuring that the welfare benefits of innovation are shared broadly among society. Policies such as antitrust rules, intellectual property regimes, and data regimes have important effects on how much competition a firm will face after engaging in an innovation.

Measurement In measuring the demand effect, firm i can take the price change ΔP_i^{II} that results from its optimal pricing strategy as exogenous to the described impact assessment or, alternatively, it can treat the price reduction ΔP_i^{II} as a choice variable that will affect whether and to what extent the productivity gains from an innovation are shared with other factor owners. In either case, the price changes need to be adjusted for changes in product quality in order to correctly measure the impact of an innovation on consumer demand and welfare – see for example Nordhaus (1998) for a detailed discussion.

The effects of the price change on demand are determined at a first-order approximation by the demand elasticity for good i,

$$\frac{\Delta C_i^{II}}{C_i} \cong \epsilon_i \frac{\Delta P_i^{II}}{P_i}$$

Given the firm's production technology, it can determine the effects of how much factor input it needs to produce the additional output, and by how much this will increase its factor bill as

$$\Delta \ell_i^{II} \cong L_Y^i \left(Y_i; w, A_i\right) \Delta C_i^{II} \quad \text{and} \quad \Delta b_i^{II} \cong w \cdot \Delta \ell_i^{II}$$

Both are additive to $\Delta \ell_i^I$ and Δb_i^I. Moreover, the change in the firm's profit is given by the difference between increases in revenue and factor costs, $\Delta \pi_i^{II} = \Delta \left(P_i^{II} Y_i^{II}\right) - \Delta b_i^{II}$.

3.3 Factor Reallocation Effect

The direct and demand effects that we have described so far represent partial equilibrium responses but do not fully describe the new equilibrium that the economy would reach after an innovation at firm i has taken place. In particular, intermediate goods producers need to adjust their production so as to absorb the factors made redundant by sector i, $d\ell_i^I + d\ell_i^{II}$, as a result of the innovation, while also satisfying the changes in consumer demand that result from the innovator's price change.

We assume that the aggregate production function $F(\cdot)$ for the economy in which the direct and demand effects of the innovation have already taken place is given as described in equation (9). In that economy, final output is given by

$F\left(L+d\ell_i^I+d\ell_i^{II}\right)$ but the factors $d\ell^{III}=-\left(d\ell_i^I+d\ell_i^{II}\right)$ need to be redeployed. When they are reallocated to the economy, final output goes up by

$$dC=F_L\left(\cdot\right)\cdot d\ell^{III}=w\cdot d\ell^{III}>0$$

This reflects that re-employing redundant factors increases output.

Similarly, the effect on factor returns is given by

$$dw=F_{LL}\left(\cdot\right)d\ell^{III} \tag{11}$$

which is equivalently captured by the elasticity $dw/w=\varepsilon_{w,L}d\ell^{III}/L$. Generally speaking, the returns on factors that are made redundant by the innovation decline, and the returns on factors that are in increasing demand go up. The effect on the total factor bill is given by $d\left(w\cdot L\right)=dw\cdot L+w\cdot d\ell^{III}=\left(w+LF_{LL}\left(\cdot\right)\right)d\ell^{III}$.

Measurement Since the detailed structure of each intermediate goods producer of the economy is not accessible to researchers, the most promising avenue for estimating the factor reallocation effect of a given innovation is to resort to the best available parameterizations of aggregate production functions. In general, the factor reallocation effect from absorbing labor $\Delta\ell^{III}=-\left(\Delta\ell_i^I+\Delta\ell_i^{II}\right)$ can be captured as

$$\begin{aligned}\Delta Y&\cong w\cdot\Delta\ell^{III}\\ \Delta w&\cong F_{LL}\left(L\right)\Delta\ell^{III}\end{aligned} \tag{12}$$

3.3.1 Transition Costs in Factor Reallocation

The above analysis performed a comparison between two equilibria – before and after the innovation – without considering the transition. If it takes time to reallocate redundant factors, then it may be desirable to take into account the associated transition costs.

We focus our analysis on the unemployed factors h that need to be redeployed so $\Delta\ell_h^{III}<0$ and exclude any factors h that are in greater demand, $\Delta\ell_h^{III}>0$, for which adjustment is likely to be swift. Therefore we consider solely the reallocation of the vector of unemployed factors $U_0=\max\left\{0,-\Delta\ell^{III}\right\}$.

Let us parameterize the rate at which unemployed factor h is redeployed by γ_h, i.e., each instant of time, a fraction γ_h of the unemployed factor pool U_h finds employment again, implying a a half-time of factor unemployment of $1/\gamma_h$.[3] The associated law of motion is given by the differential equation $\dot{U}_{t,h} = -\gamma_h U_{t,h}$, which can be solved for the path

$$U_{t,h} = U_{0,h} e^{-\gamma_h t}$$

Valuing the unemployed factor h at factor price w_h and assuming time discount rate r per time unit, the present discounted value of the transition cost T_h is given by the integral over this path

$$T_h = w_h \int_0^\infty e^{-rt} U_{t,h} dt = w_h U_{0,h} \int_0^\infty e^{-(\gamma_h + r)t} dt = \frac{w_h U_{0,h}}{\gamma_h + r}$$

This is the opportunity cost of temporary unemployment for the owners of factor h that arises from the transition to the new equilibrium. $T_h$is a present discounted value; it can also be translated into a flow cost rT_h per time period to be comparable to the losses for factor owners analyzed above, e.g., in equation (12).

4 Supply Chains and Vertical Effects

When a firm draws on significant inputs of intermediate goods so that an innovation also affects factor demand along the firm's supply chain, it is desirable to also consider how an innovation at the firm will propagate through its supply chain. We label these "vertical effects" and employ the superscript Roman numerals IV to describe them.

To capture the vertical effects of a technological innovation dA_i, we expand the baseline model by accounting for the fact that some inputs are themselves intermediate goods. In this version of our model, we add each firm j's intermediate good inputs $x_j \in \mathbb{R}^I$ to the sector j intermediate goods production function so

$$Y_j = F_j(\ell_j, x_j, A_j)$$

[3] A richer analysis of the transition in the spirit of Mortensen and Pissarides (1994)would also take into account how the incentives of employers to create factor vacancies and by extension the matching probability for unemployed factors are affected by the size of the unemployed factor pool. However, as long as the firm under consideration is small in the factor market, these considerations are exogenous, and the constant redeployment rate that we assumed is a good approximation.

The associated input demand function $N_j(Y_j, w, P; A_j)$ contains $H + I$ elements for the H factors and I intermediate goods of the economy, reflecting the cost-minimizing way of producing output Y_j at prevailing factor and intermediate goods prices. Denoting by $\nabla_Y N = (\partial N_j / \partial Y_i)$ the matrix of marginal intermediate input requirements of each intermediate good i, we find that any change in final demand for intermediate goods dC_i requires a change in the production of intermediate goods dY_i satisfying

$$dY_i = dC_i + \nabla_Y N dY_i$$

A change in consumption demand for intermediate goods of dC_i thus requires a change in total production of intermediate goods of $dY_i = (I - \nabla_Y N)^{-1} dC_i$ as given by the Leontief inverse of the production network. The total change in factor input demand arising from this change in consumption demand is then given by

$$d\ell_i^{IV} = \nabla_Y N dY_i = \nabla_Y N (I - \nabla_Y N)^{-1} dC_i$$

This defines an all-in factor input demand function $L_j(Y_{ij}, w, P; A_j)$ that accounts for the factor inputs along the organization's supply chain.

Measurement In practice, capturing changes to the all-in factor input demand resulting from an innovation is quite simple if the supply chain of firm j can be collapsed in the sense that firm j and its intermediate good inputs can be analyzed as if they were produced by a single firm. By contrast, if intermediate goods production affects other production processes than firm j, for example because it gives rise to significant synergies or returns to scale, then measurement requires sufficient knowledge about all the production processes involved. The example in section 7 considers a case in which the supply chain can be collapsed.

5 Market Structure and Horizontal Effects

Horizontal effects arise whenever there are significant effects on the producers of complements or substitutes, for example when firm i operates under monopolistic competition. The horizontal effects of a technological innovation are a function of the organization's industry structure and arise when the innovation and the resulting demand effects also impact the organization's competitors or producers of complementary goods and services.

We describe evaluate the horizontal effects of a firm's innovation by building on Example 1 of our framework in which intermediate goods entered final goods production as a CES aggregate with elasticity of substitution σ. We assume that the intermediate goods created by sector i are in turn a CES aggregate of the output of K different firms operating in monopolistic competition, with elasticity of substitution η. The case $\eta > 1$ captures the case that the firms in sector i are competitiors; the case $\eta < 1$ reflects that the products of two different firms produce complementary goods. For simplicity of language, we will refer to firm $k \neq j$ as a "competing" firm in the following, although our analysis covers both cases.

Denoting the prices and quantities of each firm k in sector i by P_{ik} and Y_{ik} and the relative size by a_{ik} where $\sum_k a_{ik} = 1$, the sector i price index is $P_i^{1-\eta} = \sum_k a_{ik}^\eta P_{ik}^{1-\eta}$, and demand for firm k output is

$$Y_{ik} = \left(\frac{P_{ik}}{a_{ik}P_i}\right)^{-\eta} \cdot Y_i = \left(\frac{P_{ik}}{a_{ik}P_i}\right)^{-\eta} \cdot \left(\frac{P_i}{a_i P}\right)^{-\sigma} \cdot Y \tag{13}$$

We observe that firm k's revenue share in sector i is given by

$$\lambda_{ik} = \frac{P_{ik}Y_{ik}}{P_i Y_i} = \frac{P_{ik}^{1-\eta} a_{ik}^\eta}{P_i^{1-\eta}} = \frac{P_{ik}^{1-\eta} a_{ik}^\eta}{\sum_h a_{ih}^\eta P_{ih}^{1-\eta}}$$

where $\sum_k \lambda_{ik} = 1$ holds by construction.

We now consider the effects of an innovation at firm j that induces the firm to lower its price by $d\log P_{ij} = dP_{ij}/dP_{ij}$. For simplicity, we assume that competing firms $k \neq j$ keep their prices unchanged in response to the innovation at firm j – this is in fact their optimal behavior under a CES structure when the technology and costs of competing firms are unchanged, although it is straightforward to employ alternative assumptions on pricing strategies. The effects of firm j's price change on the price index of sector i goods is

$$\frac{d\log P_i}{d\log P_{ij}} = \frac{a_{ik}^\eta P_{ik}^{1-\eta}}{P_i^{1-\eta}} = \lambda_{ij}$$

In other words, the decline in the price index is proportional to firm j's revenue share of sector i. The effects on demand for the output of firm j itself and its competitors $k \neq j$ is

$$\frac{d\log Y_{ij}}{d\log P_{ij}} = -\left(1-\lambda_{ij}\right)\eta - \lambda_{ij}\sigma := \epsilon_j \qquad\qquad \frac{d\log Y_{ik}}{d\log P_{ij}} = \left(\eta-\sigma\right)\lambda_{ij} \tag{14}$$

The intuition is that lowering P_{ij} by 1% reduces the relative price P_{ij}/P_i by $(1-\lambda_{ij})$%, whereas the relative price of P_{ik}/P_i for $k \neq j$ goes up by λ_{ij}%. The demand responses given in (14) then result directly from equation (13). If firms within sector i are competitors, then we generally expect that $\eta > \sigma$ so competing firms lose demand.[4]

These quantity effects give rise to changes in factor input demands of the competing firms that are captured by the sector-wide factor input demand function

$$L_i = L_j\left(Y_{ij}, w; A_j\right) + \sum_{k\neq j} L_k\left(Y_{ik}, w; A_k\right)$$

When firm j engages in an innovation, the changes in the second term of this expression correspond to the horizontal effects of firm j's innovation on factor demand,

$$d\ell_i = \underbrace{L_{j,Y}dY_{ij}}_{\text{demand effects}} + \underbrace{\sum_{k\neq j} L_{k,Y}dY_{ik}}_{\text{horizontal effects}}$$

The first term in this expression corresponds to firm j's own-demand effects $d\ell_i^{II}$, as already described in section 3.2.

Measurement Measuring the horizontal effect of an innovation requires the firm j's own reduced-form demand elasticity ϵ_j that we considered in section 3.2 as well as the firm's sectoral revenue share λ_{ij} and the reduced-form elasticity of competitors' demand $\left(\eta-\sigma\right)\lambda_{ij}$ – or the underlying structural elasticities η and σ. Given these parameters, we employ the first-order approximation for other firms $k \neq j$ in the sector

$$\frac{\Delta Y_{ik}}{Y_{ik}} \cong \left(\eta-\sigma\right)\lambda_{ij}\frac{\Delta P_{ij}}{P_{ij}}$$

[4]To square the results in equation (14) with the demand response we found in section 3.2, note that the reduced-form elasticity ϵ_i that we identified there corresponds to the full elasticity $(1-\lambda_{ij})\eta + \lambda_{ij}\sigma$ that we identified here once we account for the differences in the structure of demand.

and find the effect on firm k's factor input demand

$$\Delta \ell_{ik} \cong L_{k,Y}(\cdot)\,\Delta Y_{ik}$$

The total horizontal effects of firm j's innovation are

$$\Delta \ell_i^V = \sum_{k \neq j} \Delta \ell_{ik} \cong \sum_{k \neq j} L_{k,Y}(\cdot)\,\Delta Y_{ik}$$

If the competing firms have the same production technologies and pricing strategies so the marginals $L_{k,Y}(\cdot)$ and prices P_{ik} are identical across $k \neq j$, then we can simplify this to

$$\Delta \ell_i^V \cong L_{k,Y} \cdot (\eta - \sigma)\,\lambda_{ij} \frac{\Delta P_{ij}}{P_{ij}} \cdot \sum_{k \neq j} Y_{ik}$$

The interpretation of the three factors in this expression is that the total horizontal effects $\Delta \ell_i^V$ consist of how much a unit increase in output impacts factor demand, $L_{k,Y}(\cdot)$, times the percentage change in demand resulting from firm j's price change, $(\eta - \sigma)\,\lambda_{ij}\Delta P_{ij}/P_{ij}$, times the total quantity of output of all the competing firms, $\sum_{k \neq j} Y_{ik}$.

6 A Sample Application

This section introduce a sample application to demonstrate how to apply the framework more tangibly. Consider the fictional case of a large fast-food chain that introduces a new technology that allows it to automate a crucial task involved in burger-flipping. Pre-innovation, assume that the company earns $8bn in annual revenue and employs 200,000 unskilled fast-food workers at an average wage of $20,000 as well as 2,000 workers with a college degree at its headquarters at an average wage of $100k each. Moreover, it pays $1bn for food materials (variable costs) and $2bn for the rent and user cost of its restaurants (fixed costs). Automating the burger-flipping allows the company to produce and sell its food with 10% less labor in its restaurants, although it needs to increase its headcount at headquarters by 500 to develop and maintain the technology. As a result of the cost savings, we assume that the company decides to lower its prices by 4% to

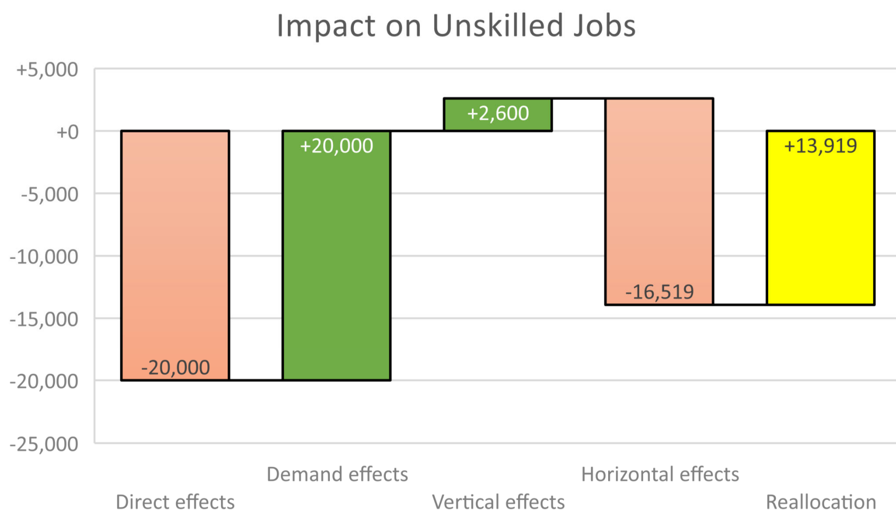

Figure 1: Adding up the effects on unskilled jobs in our sample application

increase its market share, and it projects that this will increase sales by 1/9th = 11.1%.

Figure 1 illustrates the five described effects for unskilled workers. Note that the factor reallocation effect, captured by the last bar, reflects the sum of the other effects to ensure that the market clears once all adjustments have taken place. We keep track of the calculations behind the described numbers as well as the ensuing analysis in Table 1.

1. In the given example, the **direct effects** of the innovation for the given level of production reflect the displacement of 10% or 20,000 workers of the company's unskilled workforce as well as the increase in college-degree workers by 500 at headquarters.

2. The **demand effects** that result from the company's 4% price reduction in our example amount to an increase in sales by 11.1% to a total of $8.89bn.[5] The greater product demand also increases its need for unskilled fast-food workers by 20,000, undoing the direct effects and enabling the company to increase productivity without laying off workers – in Figure 1, this implies that the sum of direct and demand effects brings us back to zero.

3. The **vertical effects** reflect that the higher demand for the company's prod-

[5]This corresponds to a reduced-form demand elasticity of $\epsilon_j = 2.77$.

	Pre-innovation	1) Direct effects		2) Demand effects		3) Vertical effects for suppliers	4) Horizontal effects for competitors
Unit price	$1.00		$1.00	-4%	$0.96		
Demand (in m units)	8,000		8,000	+11.11%	8,889	$ +111m	$ -593m
Revenue (in $m)	$ 8,000		$ 8,000		$8,533		
Unskilled workers	200,000	-10%	180,000	+11.11%	200,000	2,600	-16,519
wage bill (in $m)	$ 4,000		$ 3,600		$ 4,000	$ 51	$ -330
Skilled workers (HQ)	2,000	+25%	2,500		2,500		
wage bill (in $m)	$ 200		$ 250		$ 250		
Food Materials (in $m)	$ 1,000		$ 1,000	+11.11%	$ 1,111		
Restaurants (in $m)	$ 2,000		$ 2,000		$ 2,000		
Net Income	$ 800		$ 1,150		$ 1,172		

Table 1: Sample distributive impact assessment of a technological innovation

ucts will induce it to increase its spending on food materials. Before the increase in product demand, the company's \$8bn revenue led to \$1bn in spending on food materials. Given the labor intensity of the agricultural sector of $\alpha = .46$ (Valentinyi and Herrendorf, 2008) and assuming that the sector employs largely unskilled workers with an average wage of \$20,000, this generated \$460m expenditure on 23,000 unskilled workers pre-innovation. The 11.1% increase in product demand leads to an 11.1% increase in the demand for unskilled workers along the company's supply chain, amounting to 2600 extra workers.

4. To evaluate the **horizontal effects**, we analyze the industry structure in which the company is operation. We assume that the fast-food chain under consideration holds one third of the US market share and operates in monopolistic competition with its competitors. Based on an analysis of the competition, the company expects that two thirds of the increase in its demand are drawn from its competitors, and one third represents new demand for fast-food products. Competitors will therefore experience a revenue decline of approximately \$600m. This will reduce the all-in demand for unskilled labor at the company's competitors by about 16,500 workers.

5. The **factor reallocation** effects require that the economy needs to provide an extra $\Delta S = -500$ college-degree workers and needs to absorb an additional $\Delta U =$ 16,500 – 2600 = 13,900 unskilled workers to equilibrate the labor market, as illustrated in the last column of Figure 1. This leads to additional output of 13,900 $\times$ \$20k – 500 $\times$ \$100k = \$228m. To determine the effects on factor bills, we calibrate Cobb-Douglas factor shares of (1) skilled and (2) unskilled workers from the 2018 CPS March Supplement to $a_S = .34$ and $a_U = .26$. Rewriting the vector equation (12) line-by-line, we obtain the

overall effect on the unskilled and skilled wage bills

$$\begin{aligned}
U \cdot \Delta w_U &= -\left(1-a_U\right) w_U \cdot \Delta U + a_S w_S \Delta S \\
&= -\left(1-.26\right) \times 13,900 \times \$20k - .34 \times 500 \times \$100k \\
&= -\$206m - \$17m = -\$223m \\
S \cdot \Delta w_S &= -\left(1-a_S\right) w_S \cdot \Delta S + a_U w_U \Delta U \\
&= \left(1-.34\right) \times 500 \times \$100k + .26 \times 13,900 \times \$20k \\
&= \$33m + \$72m = \$105m
\end{aligned}$$

In words, both the reallocation of 13,900 unskilled workers away from the innovating firm and of 500 college-workers to the firm put pressure on the wages of unskilled workers, and both effects increase skilled wages.

We also conduct two experiments to study how the institutional setting in which the innovation is deployed affects the outcome of our analysis. First, we assume greater competition in the sector. In our baseline analysis, two thirds of the revenue gains of the innovating firm were at the expense of competitors. We increase the elasticity of substitution between competing firms in the sector so that five sixths of the revenue gains come from competitors while holding the reduced-form demand elasticity of the innovating firm fixed. As a result, the innovating firm's demand effects are unchanged but the horizontal effects of the innovation increase, generating revenue losses for competitors of $741m and job losses of 20,600 instead of 16,500 workers.[6]

Second, we assume a change in the structure of intellectual property rights so that the innovation by firm j is freely copied by all competing firms within the sector, reducing unit costs, prices, and employment of all firms in the sector proportionately to what we assumed in our baseline analysis for firm j above. As a result, the direct effects of the innovation on the sector are to displace 60,000 unskilled workers and create 1500 skilled jobs; the demand effects (assuming a unitary demand elasticity for the sector as a whole) create 21,600 unskilled jobs,

[6] An alternative experiment would be to hold the elasticity of substitution σ of different sectors fixed and increase solely the elasticity of substitution η of competing firms. In that case, the reduced-form demand elasticity ϵ_j of the innovating firm would increase, generating greater positive demand effects, which would be mostly offset by more negative horizontal effects, as captured by equation (14). At the margin, revenue would move from less-automated competing firms to a more-automated innovating firm, generating more modest employment losses.

and the vertical effects generate an additional 2800 jobs, giving rise to a total of 35,600 unskilled jobs destroyed instead of 16,500 in our baseline analysis. Intuitively, since the intellectual property regime considered here implies that the worker-saving innovation is rolled out across a larger part of the economy, the job impact is correspondingly larger.

7 Conclusions

This paper develops an economic framework to evaluate the effects of a technological innovation on economy-wide labor demand. I show that such an evaluation can be performed in five steps: direct effects, demand effects, vertical effects, horizontal effects, and factor reallocation effects. The described methodology is flexible so it can be easily adapted to a wide range of applications using data that is generally available in the accounting and financial planning and analysis departments of corporations.

An interesting question going forward is how a given innovation will affect the path of future innovation. There are competing effects at work. On the one hand, a “stand on the shoulders of giants” effect captures that an innovation allows for future follow-up innovations that build on it. On the other hand, the “fishing out the pool” effect captures that whenever one innovation is developed to solve one problem, the next problem will be more difficult to solve. Moreover, these effects are largely external to the organization under consideration, implying that they entail significant spillovers.

References

Acemoglu, D., Lelarge, C., and Restrepo, P. (2020). Competing with robots: Firm-level evidence from France. *AEA Papers and Proceedings*, 110:383–388.

Acemoglu, D. and Restrepo, P. (2018). The race between machine and man: Implications of technology for growth, factor shares and employment. *American Economic Review*, 108(6):1488–1542.

Acemoglu, D. and Restrepo, P. (2019). The wrong kind of AI? Artificial intelligence and the future of labour demand. *Cambridge Journal of Regions, Economy and Society*, 13(1):25–35.

Acemoglu, D. and Restrepo, P. (2021). Tasks, automation, and the rise in US wage inequality. *NBER Working Paper*, w28920.

Atkinson, A. B. and Stiglitz, J. E. (1980). *Lectures on Public Economics*. McGraw-Hill, New York.

Autor, D. (2015). Why are there still so many jobs? The history and future of workplace automation. *Journal of Economic Perspectives*, 29(3):3–30.

Autor, D. (2019). Work of the past, work of the future. *AER Papers and Proceedings*, 109:1–32.

Autor, D. and Salomons, A. (2018). Is automation labor share-displacing? productivity growth, employment, and the labor share. *Brookings Papers on Economic Activity*, 2018(1):1–87.

Berg, A., Buffie, E., and Zanna, F. (2018). Should we fear the robot revolution? (the correct answer is yes). *Journal of Monetary Economics*, 97:117–148.

Bessen, J. (2016). How computer automation affects occupations: Technology, jobs, and skills. *BU Law and Economics Working Paper*, No. 15-49.

Bostrom, N. (2014). *Superintelligence: Paths, Dangers, Strategies*. Oxford University Press.

Brynjolfsson, E., Mitchell, T., and Rock, D. (2018). What can machines learn and what does it mean for occupations and the economy? *AEA Papers and Proceedings*, 108:43–47.

Costinot, A. and Werning, I. (2018). Robots, trade, and luddism: A sufficient statistic approach to optimal technology regulation. *NBER Working Paper*, w25103.

Frey, C. B. and Osborne, M. (2013). The future of employment. *manuscript, Oxford Martin School*.

Frey, C. B. and Osborne, M. (2017). The future of employment: How susceptible are jobs to computerisation? *Technological Forecasting and Social Change*, 114:254–280.

Furman, J. and Seamans, R. (2019). AI and the economy. *Innovation Policy and the Economy*, 19(1):161–191.

Keynes, J. M. (1930). Economic possibilities for our grandchildren. In *Essays in Persuasion*, pages 358–373. Harcourt Brace, New York.

Klinova, K. (2022). Governing AI to advance shared prosperity. In Justin Bullock et al., editor, *Oxford Handbook of AI Governance*. Oxford University Press.

Klinova, K. and Korinek, A. (2021). AI and shared prosperity. *Proceedings of the 2021 AAAI/ACM Conference on AI, Ethics, and Society (AIES 2021)*.

Koch, M., Manuylov, I., and Smolka, M. (2021). Robots and firms. *The Economic Journal*, 131(638):2553–2584.

Korinek, A. and Juelfs, M. (2022). Preparing for the (non-existent?) future of work. In Justin Bullock et al., editor, *forthcoming, Oxford Handbook of AI Governance*. Oxford University Press.

Korinek, A. and Stiglitz, J. E. (2018). Artificial intelligence, worker-replacing technological progress and income distribution. *Working Paper*.

Korinek, A. and Stiglitz, J. E. (2019). Artificial intelligence and its implications for income distribution and unemployment. In Agrawal, A., Gans, J., and Goldfarb, A., editors, *The Economics of Artificial Intelligence: An Agenda*. NBER and University of Chicago Press.

Korinek, A. and Stiglitz, J. E. (2021a). Artificial intelligence, globalization, and strategies for economic development. *NBER Working Paper*, 28453.

Korinek, A. and Stiglitz, J. E. (2021b). Steering technological progress. *Working Paper*.

Lund, S., Manyika, J., Segel, L. H., Dua, A., Hancock, B., Rutherford, S., and Macon, B. (2019). The future of work in america: People and places, today and tomorrow. Technical report, McKinsey Global Institute.

Manyika, J., Lund, S., Chui, M., and et al. (2017). Jobs lost, jobs gained: What the future of work will mean for jobs, skills, and wages. Technical report, McKinsey Global Institute.

Mortensen, D. T. and Pissarides, C. A. (1994). Job creation and job destruction in the theory of unemployment. *Review of Economic Studies*, 61(3):397–415.

Nordhaus, W. (1998). Quality change in price indexes. *Journal of Economic Perspectives*, 12(1):59–68.

Tegmark, M. (2017). *Life 3.0: Being Human in the Age of Artificial Intelligence*. New York: Knopf.

Valentinyi, A. and Herrendorf, B. (2008). Measuring factor income shares at the sectoral level. *Review of Economic Dynamics*, 11(4):820–835.

A Analytic Example

This appendix provides a full analytic derivation of the different effects of a technological innovation in a version of our baseline model from Section 2 that can be solved analytically.

Assume that the production technology for final goods is given by the Cobb-Douglas production function in (2), and there are competitive intermediate goods with a constant-returns production function $A_j F_j(\ell_j)$. Each sector can thus be described by a representative firm j, and the set of firms is $\mathcal{J} = \{1, \ldots I\}$. The production function reflects that there are no intermediate goods, and the productivity parameter A_j is Hicks-neutral and scales the output generated by the factors of production proportionately.

The optimization problem for the production of final goods is to maximize (1) subject to the budget constraint $\sum_i P_i C_i \leq I$, where final goods are the numeraire. This results in demand functions for intermediate good i of

$$D_i(P_i, I) = a_i I / P_i \tag{15}$$

The optimization problem of a competitive intermediate goods producer j in sector i is to choose factor inputs to maximize profits

$$\max_{\ell_j} \Pi_j = P_i A_j F(\ell_j) - w \cdot \ell_j$$

and results in the vector of optimality conditions

$$P_i A_j F_\ell(\ell_j) = w \tag{16}$$

Since the production function F_j exhibits constant returns, its derivative F_ℓ is homogenous of degree 0 – this implies that if condition (16) is satisfied for a vector of inputs ℓ_j, it is also satisfied for the vector $\lambda \ell_j$ for any $\lambda > 0$. The vector of optimal factor input requirements $L_j(Y_j, w; A_j)$ as defined in (5) results from the dual of this maximization problem, and is given by

$$L_j(Y_j, w; A_j) = Y_j L_j^* / A_j$$

where we define by L_j^* the optimal unit factor input requirement, i.e., the combination of inputs that produces one unit $F\left(L_j^*\right) = 1$ for unit productivity and that is optimal according to condition (16). Given constant returns, it is easily verified that $A_j F\left(L_j\left(Y_j, w; A_j\right)\right) = Y_j$.

Equilibrium An equilibrium in the described economy with sectoral productivity levels $\left(A_j\right)_{j=1\ldots I}$ consists of a level C of final goods consumption, intermediate goods outputs $\left(C_i\right)_{i=1\ldots I}$, factor inputs $\left(L_h\right)_{h=1\ldots H}$ as well as intermediate goods prices $\left(P_i\right)_{i=1\ldots I}$ and factor prices $\left(w_h\right)_{h=1\ldots H}$ that solve the optimization problem of final goods producers and intermediate goods producers and that clear intermediate goods markets and factor markets $\sum_j \ell_j = L$.

Effects of Innovation Consider an equilibrium with productivity levels $\left(A_j\right)_{j=1\ldots I}$ and let us denote organization j's factor inputs before the innovation by

$$\ell_j^0 = L_j\left(Y_j, w; A_j\right)$$

and let us consider an innovation in sector j that leads to a new productivity level $A_j' > A_j$.

The **Direct Effect** capture the factor input savings from Hicks-neutral productivity growth: to produce the original level of output Y_j at given prices, the organization's factor inputs can be scaled down by A_j/A_j' to

$$\ell_j^I = L_j\left(Y_j, w; A_j'\right) = \frac{A_j}{A_j'}\ell_j^0$$

The same amount of sectoral output can now be produced with fewer factor inputs.

The **Demand Effects** capture that lower prices grow sector i demand. For given factor prices, higher productivity in sector i implies that competitive firms will reduce their prices in proportion to the productivity gains to $P_i' = P_i \cdot A_j/A_j'$. The price reduction leads to an increase in sector i goods demand that is directly proportional to the productivity gain as captured in (15), i.e., $C_i' = C_i \cdot A_j'/A_j$. Given that the production function is constant returns, the new factor input requirements scale up ℓ_j^I by the factor A_j'/A_j,

$$\ell_j^{II} = \ell_j^I \cdot \frac{A_j'}{A_j} = \ell_j^0$$

In summary, while the direct effects reduce the inputs required to produce a given amount of output, the demand effect expands demand and the inputs required to produce the new level of output.

In this version of our framework, horizontal and vertical effects are not present because we assumed a simple production structure without input-output linkages and with perfect competition in each sector. The factor reallocation effect is not present because the elasticity of demand for intermediate goods under Cobb-Douglas is unity so productivity increases generate demand effects that precisely offset the direct factor-saving effects. Total factor employment in each of the different sectors of the economy is therefore unchanged.

The higher productivity in sector j scales up the aggregate factor input demand for all factors in the economy by $\left(A'_j/A_j\right)^{a_i} > 1$ – since one of the sectors has become more productive, it can produce more output for given inputs, which raises demand for all the factors across the economy in equal proportion. The described Cobb-Douglas economy with constant-returns intermediate inputs that exhibit Hicks-neutral progress is thus a knife-edge case in which technological progress does lift all boats in equal proportion and does not redistribute between factors. The proportional increase in factor prices implies that the prices of all the other intermediate goods $i \neq j$ in the economy also rise by the factor $\left(A'_j/A_j\right)^{a_j} > 1$ since $P_i = w \cdot L_i^*/A_i \forall i$ and w rises. The overall change in the sector j intermediate goods prices is $\left(A_j/A'_j\right)^{1-a_i} < 1$.

Let us summarize these findings in the following statement:

Proposition. *Consider an equilibrium of the described economy with productivity levels $(A_j)_{j=1\ldots I}$. An increase in productivity in sector j to $A'_j > A_j$ scales up the output produced in the sector by A'_j/A_j and scales down the sector j goods price by A_j/A'_j. Moreover, it scales up all factor prices by $\left(A'_j/A_j\right)^{a_i} > 1$. It leaves the allocation of factors across intermediate goods sectors unchanged.*

Center on
Regulation and Markets
at BROOKINGS

The Center on Regulation and Markets at Brookings provides independent, non-partisan research on regulatory policy, applied broadly across microeconomic fields. It creates and promotes independent economic scholarship to inform regulatory policymaking, the regulatory process, and the efficient and equitable functioning of economic markets.

Questions about the research? Email communications@brookings.edu.
Be sure to include the title of this paper in your inquiry.