The Micro Elasticity of Substitution and Non-Neutral Technology*

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Abstract

I provide evidence on the micro elasticity of substitution between capital and labor using cross-sectional variation in local wages for identification and a comprehensive dataset of US manufacturing plants. I estimate an elasticity of substitution of 0.5 for 1987; estimates across industries mostly range between 0.4 and 0.7. I then use these elasticity estimates to separately identify labor augmenting and capital augmenting productivity. I find that labor augmenting productivity differences tend to be more persistent and more highly correlated with size and exports than capital augmenting productivity differences.

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The elasticity of substitution between capital and labor is central to many questions in economics. It governs how firms' usage of labor and capital responds to changes in factor prices due to, for example, investment subsidies (Hall and Jorgenson (1967)), tariffs on capital goods (Cai et al. (2013)), changes in trade barriers (Dornbusch et al. (1980)), investment specific technical change (Greenwood et al. (1997)), minimum wages (Aaronson and French (2007)), and firing costs (Petrin and Sivadasan (2013)). When productivity is non-neutral, and so does not affect all factors proportionally, the elasticity determines how a firm adjusts relative factor intensities when hit by a productivity shock (Hicks (1932), Sato (1975)). The elasticity is also important to understand some of the reasons why firms innovate, such as due to the scarcity of labor (Acemoglu (2010)).

In this paper, I examine the elasticity of substitution at the level of the manufacturing plant. In order to identify this elasticity, I use cross-sectional differences in wages across US localities.[1] When adjusting factors is costly for firms in the short run, the long run response to changing factor prices will be larger than the short run response. The cross-sectional approach used in this paper identifies the long run response because the wage differences across locations are highly persistent over time.

Cost minimization implies that the elasticity of substitution measures, to a first order, the response of the log of the ratio of factor costs to the log of the ratio of factor prices. I

[1] An earlier literature used cross-sectional differences in wages across countries or US localities to estimate aggregate or industry elasticities. See, for example, Arrow et al. (1961), Minasian (1961), Solow (1964), Lucas (1969), Dhrymes and Zarembka (1970), and Zarembka and Chernicoff (1971).

use this relationship to identify the elasticity; no information about output quality or prices is needed. I measure the local MSA wage as an average residual wage across individuals after controlling for observed labor quality differences. To allow for geographic differences in industry composition, I include four digit industry fixed effects.

I estimate a plant-level elasticity of substitution to be about one half for the manufacturing sector. When I allow the elasticity to vary across two digit industries, estimates range between 0.4 and 0.7 for most industries; all of the estimates are less than one. I find similar estimates on average for a set of narrowly defined industries which have plants located in almost all US MSAs.

The main identifying assumption I make is that location specific wages are uncorrelated with differences in non-neutral productivity and rental prices across plants. This assumption might be violated if more productive areas have higher wages, or if the price of capital varies across locations due to locally built capital or firm specific interest rates. I address the concern of endogenous wages by instrumenting for the local wage using Bartik (1991) instruments for labor demand, and housing price instruments for labor supply. To address the concern of correlation between rental prices and wages, I estimate the elasticity between labor and equipment capital, because structures capital is likely to have much more local construction than equipment capital. I also estimate specifications with firm fixed effects to control for differences in rental prices or productivity across firms. I find broadly similar estimates to my baseline specification in these robustness checks.

The empirical literature on the capital-labor elasticity has focused on elasticities at the industry or country level of aggregation. We know from Houthakker (1955) that elasticities can be different at different levels of aggregation; Oberfield and Raval (2014) show why the aggregate elasticity should be larger than the micro elasticity for the US. Three other papers estimate the long run micro elasticity using different sources of identifying variation. Chirinko et al. (2011) use the effects of long run movements in the user cost of capital on US public firms in order to identify the long run elasticity. Their estimate is close to mine at 0.40. Using US plant level data on equipment capital and a cointegrating regression, Caballero et al. (1995) find estimates ranging from zero to two across different manufacturing industries, with an average of about one. Doraszelski and Jaumendreu (2014) use panel variation in the ratio between labor and materials prices in a structural model in which the elasticity of substitution is equal between capital, labor, and materials, and find estimates ranging between 0.45 and 0.65.

I apply my estimates of the micro elasticity of substitution to separately identify capital augmenting from labor augmenting productivity; Hicks neutral productivity is nested as a symmetric increase in both productivities. Because I do not observe quantity produced for all plants, each measure of productivity includes demand shocks.

I then revisit some of the stylized facts of the productivity literature, allowing productivity to be non-neutral. My measure of labor augmenting productivity is significantly more persistent than capital augmenting productivity and more highly correlated with plant revenue and exports. For a subset of plants producing homogeneous products, I can separate demand shocks from productivity. Only labor augmenting productivity continues to be highly correlated with plant output for these plants after removing demand shocks. These findings suggest that labor augmenting productivity is an important dimension of firm differences in productivity.

This paper is thus related to the literature on production function estimation and productivity; the recent literature since Olley and Pakes (1996) has focused on neutral technology and the Cobb-Douglas functional form, although three recent papers also look at differences in production technology.[2] Gandhi et al. (2009) develop a methodology to estimate many production functions by using the revenue share equations, provided that productivity differences are neutral. Doraszelski and Jaumendreu (2013) build a model that generalizes the knowledge capital model by allowing R&D to affect future plant productivity. Doraszelski and Jaumendreu (2014) extend this model to include non-neutral productivity, and find that labor augmenting technical change is required to explain productivity growth for Spanish manufacturing firms.

The paper proceeds as follows: Section 1 contains a model of the firm's production problem, and Section 2 my estimates of the elasticity of substitution. Section 3 shows how

[2]For the older literature, see Fuss et al. (1978) in Fuss and McFadden, eds (1978) on different production functions, and Sato (1975) for models with non-neutral productivity. At the time comprehensive micro data was typically not available, so empirical work used aggregated data or a small set of micro data for a particular industry. A typical example is McFadden (1978), who examines a CES production function for 33 steam-electric plants. Griliches and Ringstad (1971) are an early study using a comprehensive micro dataset of Norwegian manufacturing plants.

I estimate non-neutral productivity and revisits stylized facts on productivity. Section 4 concludes. The Web Appendix contains data notes and additional work.

1 Theory

I assume a constant elasticity of substitution (CES) production function, which captures, to a first order, how a plant's relative factor costs respond to a change in relative factor prices.[3] σ is the elasticity of substitution. Plant level technology is both capital augmenting, A, and labor augmenting, B; neutral technology increases both symmetrically. An increase in labor augmenting productivity B is equivalent to having more labor. The production function for the plant is then:

$$Y = (\alpha(AK)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)(BL)^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}} \tag{1}$$

Y is the physical output produced by the plant. The distribution parameter α governs how much capital contributes to output relative to labor, and is not separately identified from the mean of A and B unless σ is one.[4] Returns to scale are constant in the above production function; in my main specifications, returns to scale affects capital costs and labor costs to the same degree and so does not affect the main dependent variable, the capital cost to labor

[3] The Cobb Douglas production function captures, to a first order, how output responds to a change in factor usage.

[4] When σ is one, we have the familiar Cobb Douglas production function; all productivity is neutral and α is the elasticity of output with respect to capital.

cost ratio.

This paper considers a value added rather than gross output production function in order to focus on the role of capital and labor. The key assumption required for my empirical approach is separability between materials and a capital-labor aggregate; the Web Appendix goes further into detail on the assumptions required and empirically examines the case of non-separability.

1.1 Cost Minimization

A cost minimizing plant sets marginal products equal to factor prices. Assuming competitive factor markets, this implies that:

$$\frac{Y}{L} = (\frac{w}{C})^{\sigma}(1-\alpha)^{-\sigma}B^{1-\sigma} \tag{2}$$

$$\frac{Y}{K} = (\frac{r}{C})^{\sigma}(\alpha)^{-\sigma}A^{1-\sigma} \tag{3}$$

where C is the marginal cost.[5] Thus, the average product of labor depends on the ratio of the wage to marginal cost through the elasticity of substitution, as well as on labor augmenting productivity B. By dividing the two equations above and rearranging, the plant capital cost

[5]The marginal cost is the Lagrange multiplier on the production function in the cost minimization problem.

to labor cost ratio, or factor cost ratio, is:

$$\frac{rK}{wL} = (\frac{B}{A})^{1-\sigma}(\frac{r}{w})^{1-\sigma}(\frac{\alpha}{1-\alpha})^{\sigma} \tag{4}$$

I use the above equation to estimate the elasticity of substitution σ. Wage increases reduce the factor cost ratio when σ is less than one, and increase the factor cost ratio when σ is greater than one.

The elasticity of substitution also determines how productivity affects the plant factor cost ratio; the elasticity of the factor cost ratio to changes in labor augmenting productivity B is $1 - \sigma$. The intuition is the following. When capital and labor are complementary, so σ is less than one, an increase in the amount of labor raises the marginal product of capital relative to that of labor. An increase in labor augmenting productivity B is akin to more labor. The plant responds to the increased relative marginal product of capital by increasing capital relative to labor until relative marginal products again equal relative factor prices. The opposite effects hold when σ is above one, so capital and labor are substitutes. Neutral productivity has no effect on the factor cost ratio.

1.2 Profit Maximization

I impose a demand structure to derive plant sales and average revenue products, and their relationship to factor prices and productivities. Each plant produces a differentiated product with an isoelastic demand curve:

$$Y = \frac{D^{\varepsilon-1}}{P^{\varepsilon}} \tag{5}$$

D is a demand shifter. ε denotes the elasticity of demand for the plant's product, and is above one as required for plant price setting. The optimal price is a constant markup over marginal cost C:

$$P = \frac{\varepsilon}{\varepsilon-1}C \tag{6}$$

By combining equation (6) and equation (2), the average revenue product of labor is:

$$\frac{PY}{L} = (\frac{\varepsilon}{\varepsilon-1})^{1-\sigma} w^{\sigma} P^{1+\sigma} (1-\alpha)^{-\sigma} B^{1-\sigma} \tag{7}$$

We can see how the price depends upon the wage through the plant's marginal cost, which under cost minimization is:[6]

$$C = \left[\alpha^{\sigma}(\frac{r}{A})^{1-\sigma} + (1-\alpha)^{\sigma}(\frac{w}{B})^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \tag{8}$$

Thus, the marginal cost is a non-linear function of the wage that depends upon the elasticity

[6]To obtain the marginal cost, substitute in the first order conditions for labor and capital into the production function and then solve for the Lagrange multiplier.

of substitution.

Replacing the output price with the marginal cost in the expression for the average revenue products, the average revenue products of each factor are:

$$\frac{PY}{L} = \frac{\varepsilon}{\varepsilon-1}w\left[(\frac{\alpha}{1-\alpha})^{\sigma}(\frac{B}{A}\frac{r}{w})^{1-\sigma}+1\right] \tag{9}$$

$$\frac{PY}{K} = \frac{\varepsilon}{\varepsilon-1}r\left[(\frac{1-\alpha}{\alpha})^{\sigma}(\frac{A}{B}\frac{w}{r})^{1-\sigma}+1\right] \tag{10}$$

Labor augmenting productivity shifts the average revenue products of labor and capital in opposite directions. When the elasticity of substitution is less than one, higher labor augmenting productivity B decreases its average revenue product of capital and increases the plant's average revenue product of labor. Capital augmenting productivity has the opposite effects. The demand shifter D and neutral productivity do not shift average revenue products, because increases in either variable induce the plant to produce more until the marginal return of factors equals factor prices. This increase in production pushes the plant down its demand curve until its price falls and average revenue products remain constant.

Plant revenue is then:

$$PY = \left[\frac{D(\frac{\varepsilon-1}{\varepsilon})}{\left[\alpha^{\sigma}(\frac{r}{A})^{1-\sigma}+(1-\alpha)^{\sigma}(\frac{w}{B})^{1-\sigma}\right]^{\frac{1}{1-\sigma}}}\right]^{\varepsilon-1} \tag{11}$$

Both types of productivity increase plant revenue, so the relationship between the factor cost ratio and revenue depends upon the direction of productivity differences. The demand shifter D is isomorphic to neutral productivity; one can not tell whether a given product is produced with greater neutral efficiency or just has higher demand D.

2 Elasticity of Substitution

I identify the elasticity of substitution by using the log-linear relationship between the plant factor cost ratio and plant factor prices from equation (4):

$$\log(\frac{rK}{wL}) = -(1-\sigma)\log(\frac{w}{r}) + (1-\sigma)\log(\frac{B}{A}) + \sigma\log\frac{\alpha}{1-\alpha} \tag{12}$$

This approach does not require data on plant output prices. It does require data on both labor and capital; I cannot use one minus the labor share of revenue to proxy for the capital share because plants earn profits after payments to factors in my model.

I use cross-sectional variation in the local wage for identification. The local wage is a skill price: plants with higher plant level wages in the same location are assumed to have higher skilled workers. By using the local wage instead of the plant wage, I avoid biases from division bias and plant level skill differences. As I show in the next section, these local wage differences are highly persistent across time, which should ensure that I identify the long run elasticity. For consistent estimates, the local wage must be orthogonal to the plant rental rate for capital and the ratio of labor augmenting to capital augmenting productivity.

2.1 Data

For plant factor costs, I use the 1987 and 1997 US Censuses of Manufactures, which are censuses of all US manufacturing plants taken every five years. Following common practice in the literature, I remove Administrative Record plants, which are typically less than five employees and lack data on capital or output. A typical Census sample has more than 180,000 plants and considerable variation across plant age, location, and industry, which I use to control for confounding factors in my empirical specifications.[7]

I measure labor costs as the total salaries and wages for the plant. I measure capital by the end year book value of capital, deflated using a current cost to historic cost deflator. For 1987, I construct capital stocks for equipment and structures capital separately. I multiply these capital stocks by the appropriate rental rates using a set of two digit BLS rental rates to construct capital costs.[8] In the Web Appendix, I construct permanent inventory measures of capital using plants in the panel Annual Survey of Manufactures (ASM) and find similar estimates of the elasticity of substitution to those using the overall Census.

I measure local area wages through two independent data sources. My first source of wages is the Census five percent samples of Americans available from Ruggles et al. (2010). These surveys collect information on a wide range of attributes for a large sample of workers. I

[7] I drop manufacturing plants with missing or outlier data from my main estimates, although my results are not sensitive to these outlier corrections. I detail these procedures in the Web Appendix.

[8] The BLS measures are based on NIPA data on the ratio of capital income to capital stock. In Oberfield and Raval (2014), I develop an alternative series of rental rates based on Harper et al. (1989). Since both the capital deflator and rental rate are fixed within industry for a given year, however, these are often captured in industry fixed effects. These measures of capital costs do not include industry rental payments.

calculate the individual wage as wage and salary income divided by the total hours worked for prime age private sector men. The finest grain local area is the MSA. I control for differences in worker quality across areas by measuring the MSA wage as the average residual log wage after controlling for education, experience, industry, occupation, and race of workers.[9] The correlation in the log wage between 1990 and 2000 across all MSAs is 0.90; wage differences across locations are persistent.

My second source of local wages is the Longitudinal Business Database (LBD), which contains yearly employment and payroll data for all US establishments. I define the wage as payroll divided by employment, and construct average log wages for each county in the United States. LBD wages allow me to match wages to plants not located in MSAs, but do not permit adjustment for worker quality differences.

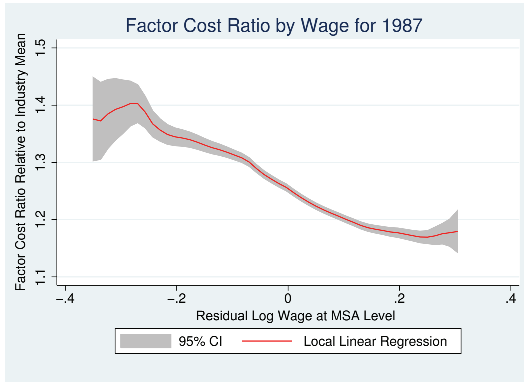
2.2 Estimates

Figure 1 depicts how the industry demeaned factor cost ratio varies with the MSA level wage in 1987. The factor cost ratio falls by 20 percent as the wage increases by about 40 percent, indicating an elasticity of substitution close to a half.

The relationship between the logged values of the factor cost ratio and local area wage is approximately linear, as a constant elasticity of substitution would imply. Table I contains

[9] These attributes explain 27.0 percent of the individual wage variation in 1987 and 26.7 percent in 1997, after which MSA differences account for 3.4 percent of the residual wage variation in 1987 and 2.4 percent in 1997. Since the Population Census is only conducted every ten years, I match the 1990 Population Census to the 1987 Census of Manufactures and the 2000 Population Census to the 1997 Census of Manufactures. The Web Appendix contains the details of these procedures.

Figure 1 Factor Cost Ratio by MSA Level Wage for 1987



Note: The graph depicts the local linear regression of plant factor cost ratio relative to the industry mean against the log MSA wage adjusted for worker characteristics.

estimates of the elasticity of substitution across all manufacturing industries after imposing linearity using both sources of wages. I control for differences in industry composition through four digit SIC industry fixed effects. I cluster standard errors at the two digit SIC-local area level, which adjusts standard errors for correlated shocks in local areas for plants in the same broad industry. For example, all plants in the transportation industry in Detroit can be affected by the same shock.[10] I also control for age and plant multiunit status.

Table I Elasticities of Substitution between Labor and Capital for Manufacturing

	MSA Level	County Level
1987	0.52 *(0.04)*	0.65 *(0.03)*
1997	0.46 *(0.03)*	0.67 *(0.01)*
Source of Wage Data	Worker Data	Establishment Data
N	≈ 125,000	≈ 180,000

Note: All regressions are of the log factor cost ratio on log local area wage, with age fixed effects, a multi-unit status indicator, and industry fixed effects as controls. Standard errors are clustered at the two digit industry-area level.

[10] With 299 MSAs in 1990 and 19 two digit industries, the maximum number of clusters is 5681.

My estimates of the elasticity of substitution from the MSA wage regressions are 0.52 in 1987 and 0.46 in 1997. Using the county wages from establishment data, my estimates of the elasticity of substitution are 0.65 in 1987 and 0.67 in 1997. These estimates are precise.

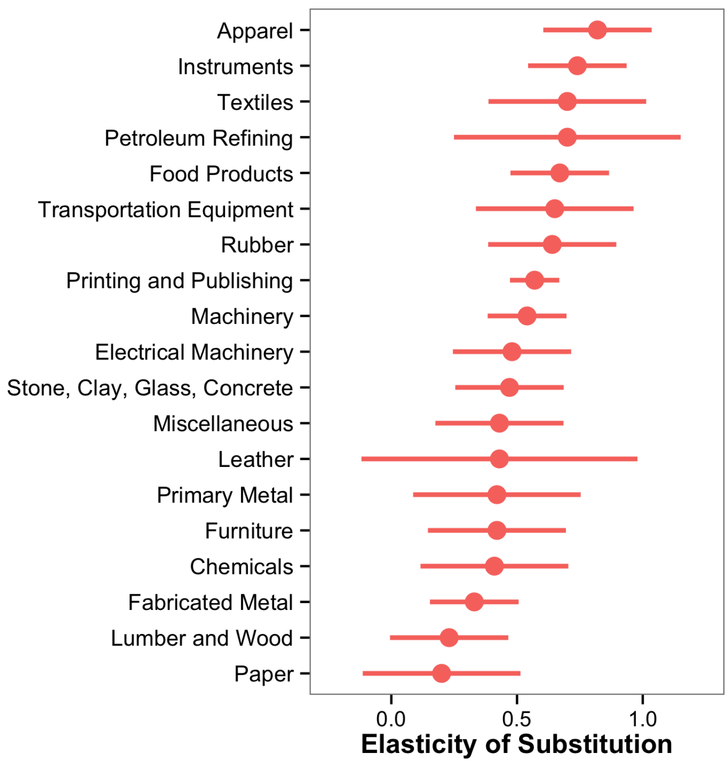
Estimates that use wages from worker data are below the estimates that use wages from establishment data. The main reason for this difference is that the worker based wages adjust for worker quality differences, which lowers the degree of wage variation across areas. If I do not adjust the wages from worker data for worker quality differences, the estimates of the elasticity of substitution are 0.62 in 1987 and 1997, similar to the estimates above using wages from establishment data.

I further estimate the elasticity of substitution at the SIC two digit level to examine the sensitivity of the elasticity of substitution to industry. I find estimates similar to those for the entire manufacturing sector. Figure 2 displays estimates and 95 percent confidence intervals of the elasticity of substitution for each two digit SIC industry for 1987 using worker based wages.[11] Most of the estimates are concentrated in a narrow band between 0.40 and 0.70; in 1987, 15 out of the 19 estimates are in this band. The elasticity of substitution is below one for all industries, and I can reject that the elasticity of substitution is one for 15 of 19 industries. Table A1 has the full set of estimates.[12]

[11] I exclude the tobacco industry (SIC 21) from the table because it is much smaller than the other two digit industries.

[12] These estimates show a bias-variance tradeoff; while the MSA estimates are lower on average for the reasons mentioned above, they tend to be noisier. The correlation between MSA estimates in 1990 and 2000 is 0.43, relative to 0.79 for the county estimates.

Figure 2 Elasticity of Substitution by Industry for 1987



Note: The figure plots estimates of the elasticity of substitution by two digit SIC industry, as well as 95 percent confidence intervals. Estimates are for 1987 using worker based MSA wages.

2.3 Robustness

Lucas (1969) had identified a number of biases in the early cross-section literature due to differences in output prices, worker quality, productivity, and industry composition across areas. I have tried to account for these biases in my baseline estimates. By using the capital cost to labor cost ratio, my specification does not depend upon output prices. Four digit industry fixed effects allow industry composition to vary across areas. My main measure of the local wage removes observed labor quality differences. Nevertheless, my identification strategy requires that the local area wage is orthogonal to differences in the rental rate of capital and plant level productivity across areas. I now discuss a number of robustness checks focused on examining these assumptions.

2.3.1 Exogenous Wage Variation

One concern is that productivity differences affect local wages. If highly productive areas have high wages and high labor augmenting productivity, my estimates of the elasticity of substitution would be biased upwards. I examine the salience of this bias through two different instrumental variables for the local wage.

The first instrument varies labor demand through how national level industry shocks affect locations with different initial industries. As in Bartik (1991), I define this instrument as the predicted local employment growth from the interaction between initial MSA employment shares of industries and the 10 year national employment growth rate of these industries.[13] I restrict the instrument to non-manufacturing industries to avoid any correlation between plant productivity shocks and national level industry demand shocks. The first column of Table II contains estimates of the elasticity of substitution using these instruments. I use wages from establishment data for the same Census year to match the instrument timing. While these wages do not control for differences in individual worker characteristics, the instrument should be orthogonal to the measurement error in wages.[14] Both of the labor demand IV estimates are close to one-half and are similar to the baseline least squares estimates.

I also instrument for labor supply through proxies for the local area cost of living. If everyone could costlessly adjust their location, workers would move until the real wage faced by workers equalized across locations. High cost of living areas would have higher nominal wages in equilibrium. I use housing and rental prices as proxies for cost of living differences, and calculate these prices using Population Census data as average MSA level residuals after controlling for housing characteristics.[15] Housing prices serve as an instrument to the extent that they are determined in equilibrium by differences in geography or regulation that impact

[13] Formally, the instrument is constructed as follows: Let $g_n(t) = \frac{1}{10}\ln(L_n(t)/L_n(t-10))$ be the national growth rate of industry n, and let $\omega_{j,n}(t)$ be the share of MSA j's employment working in industry j. Finally, the instrument is the interaction between initial MSA employment shares and 10 year national employment growth rates: $Z_j(t) = \sum_{n\in N^S}\omega_{j,n}(t-10)g_n(t)$, where N^S is the set of non-manufacturing four-digit SIC industries.

[14] Because the SIC industry definitions changed from 1972 SIC basis to 1987 SIC basis in 1987, for 1987 I use the 1976-1986 instrument.

[15] The Web Appendix contains the details of this procedure.

housing supply, or differences in amenities or industry demand and productivity outside of manufacturing that affect housing demand.

I then instrument the worker based MSA wages with current housing prices and rents together with their ten year lead and lag values to avoid cyclical variation in housing markets. The second column of Table II contains these estimates. My estimates of the elasticity of substitution are 0.34 in 1987 and 0.38 in 1997, slightly lower than my baseline estimates.

Table II Robustness Checks for Plant Capital-Labor Substitution Elasticity

	Bartik Instrument	Housing Instruments	Firm FE	Equipment Capital	State FE
1987	0.49 *(0.05)*	0.34 *(0.03)*	0.49 *(0.05)*	0.53 *(0.03)*	0.48 *(0.05)*
1997	0.52 *(0.08)*	0.38 *(0.05)*	0.48 *(0.08)*		0.46 *(0.04)*

Note: Standard errors are in parentheses. All regressions include industry dummies, age fixed effects, and a multiunit status indicator. Labor demand instruments and housing price and rent instruments are as defined in the text; housing price and rent instruments include matching year and the 10 year lag and lead. For 1997, the lead housing price or rent is not available. Wages used are the average log wage for the MSA based on workers from the Census 5 percent samples, except for the labor demand IV specification which use establishment based wages.

2.3.2 Rental Rate of Capital

Any systematic correlation between the rental rate of capital and local wage would bias my estimates. These might be correlated if the capital of the plant was produced in the same locality as the plant, so local labor and materials were factors in its production. Since locally constructed capital is more likely for buildings than equipment, I examine the elasticity of substitution between labor and equipment capital alone for 1987 to control for rental rate differences across local areas stemming from structures capital. The elasticity between labor and equipment capital is 0.53 using the quality adjusted worker wages, almost identical to the estimates using the full capital stock.

The cost of capital could also vary across firms because of differences in lending rates from banks in different locations, or from differences in firm creditworthiness. I include firm fixed effects for plants that belong to multiunit firms to control for variation in the firm rental rate of capital. These firm fixed effects also control for firm level productivity differences. The third column in Table II reports these estimates. The estimates of the elasticity of substitution with firm fixed effects are 0.49 in 1987 and 0.48 in 1997 and are similar to my baseline estimates.

2.3.3 Regulation

Regulations could also vary across local areas that affect both plant productivity and rental prices. For example, states vary in their regulations towards unions, such as right to work laws, and some states provide investment tax subsidies. I control for any such state level differences by including state level fixed effects in the last column of Table II; the elasticity of substitution for 1987 falls only slightly from 0.52 to 0.48.

2.3.4 Industry Clustering and Selection

I have assumed that plant level productivity is uncorrelated with the prevailing wage in the area that the plant locates. However, firms in an industry often co-locate within a few clusters; Detroit is synonymous with the automotive industry and Silicon Valley with the computer industry. If plants with high labor augmenting productivity cluster in areas with high wages, or agglomeration effects increase the productivity of plants within a cluster, the resulting correlation between productivity and the local wage would bias my estimates upwards. Similarly, plants outside the industry cluster could serve a different segment of the industry than plants within the cluster.

I assess the impact of selection by estimating the elasticity of substitution for a set of ten large four digit SIC industries located in almost all US MSAs and states.[16] Ready Mixed Concrete is perhaps the best test case of these industries; since ready mixed concrete cannot be shipped very far, every location must have concrete plants to supply the construction sector. Elasticities for the unclustered industries are similar to my baseline estimates, with average elasticities of 0.49 for 1987 and 0.61 for 1997 using the MSA wages, or 0.70 and 0.71 using the establishment wages. Table A2 has the full set of estimates.[17]

[16]These industries are: Newspaper Publishing (2711), Commercial Printing, Lithographic (2752), Concrete Products, Except Block and Brick (3272), Ready Mixed Concrete (3273), Fabricated Structural Metal (3441), Sheet Metal Work (3444), Bread and other Bakery Products, except Crackers (2051), Sawmills and Planing Mills (2421), Millwork (2431), and Wood Kitchen Cabinets (2434).

[17]The weights across industries are as in Oberfield and Raval (2014) and primarily depend upon overall industry size. I can reject an elasticity of one for eight out of ten industries with the MSA worker based wages and for ten out of ten industries with the county level establishment based wages in 1987. For ready mixed concrete, I find an elasticity of substitution of 0.36 in 1987 and 0.98 in 1997 using the worker based MSA wages, and 0.77 in 1987 and 0.62 in 1997 using the county level establishment wages.

3 Non-Neutral Productivity Differences

My estimates of the elasticity of substitution allow me to recover plant productivity. Cost minimization implies that each factor augmenting productivity is a function of the average quantity product of the factor and the factor share[18] :

$$\log A = \log(Y/K) - \frac{\sigma}{1-\sigma}\log(\frac{rK}{rK+wL}) \quad (13)$$

$$\log B = \log(Y/L) - \frac{\sigma}{1-\sigma}\log(\frac{wL}{rK+wL}) \quad (14)$$

For most plants in my sample, I only have measures of revenue and not quantity produced, so I cannot construct A and B as above. Instead, I invert revenue to obtain quantity produced; under isoelastic demand, optimal price setting behavior implies that the markup over marginal cost is equal to $\frac{\varepsilon}{\varepsilon-1}$. This inversion means that measures of capital and labor augmenting productivity also include demand shocks:

$$\log A + \log D = \frac{\varepsilon}{\varepsilon-1}\log(PY) - \log(K) - \frac{\sigma}{1-\sigma}\log(\frac{rK}{rK+wL}) \quad (15)$$

$$\log B + \log D = \frac{\varepsilon}{\varepsilon-1}\log(PY) - \log(L) - \frac{\sigma}{1-\sigma}\log(\frac{wL}{rK+wL}) \quad (16)$$

[18] I subsume α into labor augmenting productivity B, as is possible without loss of generality when the elasticity of substitution is less than one. The amount of labor L is the wage bill after accounting for the local wage, as is consistent with my assumption that the local wage functions as a skill price. Substitute equation (4) into the CES production function divided by the relevant factor to obtain these expressions.

I set the elasticity of substitution σ to 0.52, my baseline estimate for manufacturing in 1987. I obtain the elasticity of demand by inverting the average markup.[19] My estimates of the elasticity of demand are 3.94 in 1987 and 4.04 in 1997; I use the 1987 value for the productivity estimates.[20]

Capital augmenting and labor augmenting productivity are only slightly correlated; in 1987, the correlation between $\log A + \log D$ and $\log B + \log D$ is 0.14. I now revisit some of the standard relationships between productivity and plant level variables using these productivity measures.

3.1 Persistence

Labor augmenting productivity is substantially more persistent than capital augmenting productivity. Table III contains estimates of the ten year autocorrelation of productivity between the 1987 and 1997 Manufacturing Censuses. Capital augmenting productivity together with the demand shock has a ten year autocorrelation of 0.27, or 0.31 after weighting plants by value added. Labor augmenting productivity is much more highly correlated over time, with a 10 year autocorrelation of 0.52 in the unweighted regressions and 0.74 in the weighted regressions. The implied one year AR(1) coefficients for labor augmenting productivity range

[19] I define the markup as revenue divided by total costs from all factors, including materials. Isoelastic demand together with profit maximization imply that all plants should set the same markup, so I use the average markup for manufacturing.

[20] Oberfield and Raval (2014) examines the robustness of these demand elasticity estimates by comparing them to alternative estimates from demand estimation on a subset of industries.

between 0.94 to 0.97, compared to 0.87 to 0.89 for capital augmenting productivity.[21]

Table III Autocorrelation of Productivity

	Ten Year Persistence	
Log(A) + Log(D)	0.27 *(0.004)*	0.31 *(0.004)*
Log(B) + Log(D)	0.52 *(0.003)*	0.74 *(0.003)*
Weights	No	Value Added

Note: All regressions contain four digit SIC industry fixed effects.

3.2 Exports

The trade literature has found that exporting plants are both more capital intense and more productive (Bernard et al. (2007)). Labor augmenting productivity differences could be the cause of both facts. To examine the correlations between exports and productivity, I run regressions of labor and capital augmenting productivity on logged exports, excluding non exporters. Productivity is the dependent variable so measurement errors in productivity do not bias the coefficients. Table IV contains the coefficients on log exports.

Labor augmenting productivity is more strongly correlated with exports than capital augmenting productivity. In 1987, a plant with twice as high exports has an average 19 percent higher labor augmenting productivity B, or 16 percent higher in the value added weighted regressions. Capital augmenting productivity has a much lower correlation with exports. A plant with double the exports has on average 4 percent higher productivity in the 1987 unweighted regressions and 5 percent higher productivity in the 1987 weighted

[21]Under an AR(1) model the one year coefficient is the ten year coefficient to the power $\frac{1}{10}$.

regressions.

Table IV Correlations between Productivity and Exports

	1987		1997	
Log(A)+Log(D)	0.04 *(0.004)*	0.05 *(0.003)*	0.008 *(0.004)*	0.06 *(0.003)*
Log(B)+Log(D)	0.19 *(0.002)*	0.16 *(0.002)*	0.19 *(0.002)*	0.19 *(0.002)*
Weights	No	Value Added	No	Value Added

Note: All regressions contain 4 digit SIC industry fixed effects. The log of exports is the independent variable and a measure of productivity the dependent variable. All plants without exports are excluded from the estimates.

3.3 Correlation with Size

The theory in Section 1 implies that both capital and labor augmenting productivity should increase plant revenue. The strength of the correlation of each productivity with sales depends on whether productivity differences are primarily labor or capital augmenting. In Table V, I examine how productivity varies with plant value added. Labor augmenting productivity is more highly correlated with value added than capital augmenting productivity. A plant with twice the value added has 31 percent higher capital augmenting productivity in the unweighted regressions and 26 percent higher in the weighted regressions for 1987, compared to an average 46 and 47 percent higher labor augmenting productivity.

In all of the above results, both measures of productivity included the effect of demand shocks. For the sample of homogeneous products examined by Foster et al. (2008), I can separate demand shocks from productivity. For each of these products, I construct quantity

Table V Correlations between Productivity and Value Added

	1987		1997	
Log(A)+Log(D)	0.31 *(0.002)*	0.26 *(0.002)*	0.33 *(0.003)*	0.26 *(0.002)*
Log(B)+Log(D)	0.46 *(0.001)*	0.47 *(0.001)*	0.46 *(0.001)*	0.53 *(0.001)*
Weights	No	Value Added	No	Value Added

Note: All regressions are a measure of productivity on the log of value added, controlling for 4 digit SIC industry fixed effects.

produced and then measure productivities A and B directly as in equations 13 and 14.[22]

Table VI contains estimates for these industries.[23] Labor augmenting productivity B is correlated with both quantity produced and sales; a plant with double the quantity produced has an average 21 percent higher labor augmenting productivity in the unweighted regressions and 26 percent higher in the weighted regressions. Capital augmenting productivity is negatively correlated with quantity produced. A plant with double the quantity produced has an average 3 percent lower capital augmenting productivity in the unweighted regressions and 29 percent lower in the weighted regressions. Correlations with sales for both productivities are similar.

The combination of capital augmenting productivity and demand shocks is always positively correlated with both quantity and sales. After excluding demand shocks, only labor augmenting productivity is correlated with plant size.

[22] I have data on eleven such products: Boxes, Bread, Carbon Black, Coffee, Concrete, Flooring, Gasoline, Block Ice, Processed Ice, Plywood, and Sugar. The Web Appendix contains the details of the construction of quantity and sales for these products.

[23] I include product year fixed effects to allow each product to have an average level of capital intensity that varies by Census year and pool data over 1987, 1992, and 1997.

Table VI Correlations between Productivity and Size Using Homogeneous Products

	Log(Y)		Log(PY)	
Log(A)+Log(D)	0.80 *(0.02)*	0.12 *(0.02)*	0.67 *(0.02)*	0.15 *(0.02)*
Log(A)	-0.03 *(0.02)*	-0.29 *(0.02)*	0.04 *(0.02)*	-0.15 *(0.02)*
Log(B)	0.21 *(0.01)*	0.26 *(0.01)*	0.28 *(0.01)*	0.29 *(0.01)*
Weights	No	Value Added	No	Value Added

Note: All regressions contain product year fixed effects. The dependent variable is a measure of productivity and the independent variable either the log of quantity produced or log of sales. Standard errors here are clustered at the manufacturing plant level.

4 Conclusion

This paper has identified the micro elasticity of substitution using differences in wages across local areas in the US. Because these wage differences have been persistent over time, this identification strategy recovers the long run micro elasticity. I then estimated that the elasticity of substitution is near one-half for manufacturing. When I allowed the elasticity to vary across industries, the estimates remained close to one-half, with most ranging between 0.4 and 0.7. These estimates held up to a number of robustness checks, including instruments for the local wage, controls for firm level differences in productivity or rental prices, state-level differences in regulation, and examination of a set of narrowly defined unclustered industries.

I then used these estimates of the elasticity to separately identify labor augmenting and capital augmenting productivity. I found that the measure of labor augmenting productivity is highly persistent and more strongly correlated with plant value added and exports than capital augmenting productivity. These results point to labor augmenting productivity as an important dimension of productivity, and improve our understanding of how productivity affects firms.

This paper has examined only the micro elasticity of substitution between capital and labor. The cross-sectional identification strategy used in this paper could also be used to understand the substitution possibilities of intermediate inputs with capital and labor, and of different varieties of labor with each other and other inputs.

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Table A1 Elasticities of Substitution between Labor and Capital for Two Digit Industries

Industry	MSA Level 1987	MSA Level 1997	County Level 1987	County Level 1997	N
20: Food Products	0.67 *(0.10)*	0.87 *(0.11)*	0.71 *(0.04)*	0.81 *(0.04)*	≈ 10,000
22: Textiles	0.70 *(0.16)*	0.30 *(0.24)*	0.70 *(0.08)*	0.50 *(0.07)*	≈ 3,500
23: Apparel	0.82 *(0.11)*	0.40 *(0.09)*	1.03 *(0.04)*	0.83 *(0.03)*	≈ 12,000
24: Lumber and Wood	0.23 *(0.12)*	0.48 *(0.11)*	0.43 *(0.04)*	0.53 *(0.04)*	≈ 15,000
25: Furniture	0.42 *(0.14)*	0.18 *(0.17)*	0.47 *(0.05)*	0.49 *(0.06)*	≈ 6,000
26: Paper	0.20 *(0.16)*	0.20 *(0.15)*	0.46 *(0.06)*	0.61 *(0.05)*	≈ 4,000
27: Printing and Publishing	0.57 *(0.05)*	0.50 *(0.08)*	0.69 *(0.03)*	0.66 *(0.03)*	≈ 26,000
28: Chemicals	0.41 *(0.15)*	0.51 *(0.21)*	0.52 *(0.08)*	0.54 *(0.08)*	≈ 6,500
29: Petroleum Refining	0.70 *(0.23)*	0.53 *(0.28)*	0.80 *(0.11)*	0.81 *(0.11)*	≈ 1,500
30: Rubber	0.64 *(0.13)*	0.42 *(0.14)*	0.60 *(0.05)*	0.59 *(0.04)*	≈ 8,500
31: Leather	0.43 *(0.28)*	0.46 *(0.36)*	0.88 *(0.12)*	0.99 *(0.12)*	≈ 1,000
32: Stone, Clay, Glass, Concrete	0.47 *(0.11)*	0.80 *(0.16)*	0.64 *(0.04)*	0.58 *(0.05)*	≈ 9,000
33: Primary Metal	0.42 *(0.17)*	0.26 *(0.19)*	0.69 *(0.06)*	0.67 *(0.07)*	≈ 4,000
34: Fabricated Metal	0.33 *(0.09)*	0.25 *(0.09)*	0.56 *(0.04)*	0.59 *(0.04)*	≈ 20,000
35: Machinery	0.54 *(0.08)*	0.52 *(0.11)*	0.68 *(0.02)*	0.70 *(0.03)*	≈ 25,000
36: Electrical Machinery	0.48 *(0.12)*	0.51 *(0.12)*	0.65 *(0.07)*	0.70 *(0.05)*	≈ 8,000
37: Transportation Equip	0.65 *(0.16)*	0.77 *(0.16)*	0.70 *(0.06)*	0.75 *(0.06)*	≈ 5,000
38: Instruments	0.74 *(0.10)*	0.71 *(0.13)*	0.67 *(0.07)*	0.74 *(0.07)*	≈ 4,500
39: Misc	0.43 *(0.13)*	0.38 *(0.12)*	0.54 *(0.04)*	0.53 *(0.05)*	≈ 6,500
Source of Wage Data	Worker Data		Establishment Data		

Note: All regressions include 4 digit SIC industry fixed effects, age fixed effects, and a multiunit status indicator and have standard errors clustered at the two digit industry-area level. Wages are as defined in the text.

Table A2 Elasticities of Substitution between Labor and Capital for Large Four Digit Industries

	MSA Level		County Level		
Industry	1987	1997	1987	1997	N
2711: Newspaper Publishing	0.43 *(0.20)*	NA	0.82 *(0.07)*	NA	≈ 4,000
2752: Commercial Printing, Lithographic	0.69 *(0.07)*	0.52 *(0.09)*	0.72 *(0.03)*	0.67 *(0.04)*	≈ 12,000
3272: Concrete Products, Except Block and Brick	0.41 *(0.20)*	0.87 *(0.39)*	0.49 *(0.10)*	0.49 *(0.10)*	≈ 2,000
3273: Ready Mixed Concrete	0.36 *(0.17)*	0.98 *(0.24)*	0.77 *(0.07)*	0.62 *(0.07)*	≈ 4,000
3441: Fabricated Structural Metal	0.35 *(0.18)*	0.58 *(0.26)*	0.52 *(0.10)*	0.75 *(0.10)*	≈ 1,500
3444: Sheet Metal Work	0.65 *(0.19)*	0.28 *(0.20)*	0.55 *(0.09)*	0.58 *(0.07)*	≈ 3,000
2051: Bread and other Bakery Products	0.91 *(0.24)*	1.17 *(0.24)*	0.71 *(0.12)*	0.99 *(0.13)*	≈ 1,000
2421: Sawmills and Planing Mills	0.13 *(0.32)*	0.11 *(0.29)*	0.74 *(0.08)*	0.80 *(0.09)*	≈ 3,000
2431: Millwork	0.04 *(0.24)*	0.49 *(0.23)*	0.11 *(0.09)*	0.51 *(0.09)*	≈ 1,500
2434: Wood Kitchen Cabinets	0.26 *(0.23)*	0.66 *(0.24)*	0.31 *(0.11)*	0.60 *(0.09)*	≈ 2,000
Source of Wage Data	Worker Data		Establishment Data		

Note: All regressions include 4 digit SIC industry fixed effects, age fixed effects, and a multiunit status indicator and have standard errors clustered at the two digit industry-area level. Wages are as defined in the text.