General Purpose Technologies: engines of change?

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ABSTRACT

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This dissertation examines the relevance of technology in explaining structural and cyclical changes in the labor and product markets. The first chapter focuses on computers and the labor market, the second chapter on electricity and the labor market, and the third chapter focuses on computers and the goods market.

The three chapters rely on a General Purpose Technology and on the distinction between routine and nonroutine jobs. A General Purpose Technology has three characteristics: it has pervasive use in all industries, it improves over time, and it is able to foster other innovations. This dissertation considers the technology of computers in the second half of the 20th century and electricity in the first half. It defines "pervasive use" as the technology's ability to substitute for some types of jobs—called routine jobs—more than others. Routine jobs consist of repetitive tasks, follow an explicit set of rules, and can easily be automated by the technology. Nonroutine jobs are the remaining jobs, which cannot be easily replaced by the technology. For computers, examples of routine jobs are clerks and secretaries, since their work can be automated with information processing software, whereas examples of nonroutine jobs are managers and health aides, since their work requires creativity or personal interactions. For electricity, examples of routine jobs are laborers on the factory floor, since their work can be automated by the conveyor belt, whereas examples of nonroutine jobs are foremen and engineers, since their work requires attention or detailed calculations. The distinction between routine and nonroutine jobs depends on the technology: accountants can be nonroutine relative to electricity and routine relative to computers.

The first chapter examines computers as a theoretical explanation for changes in the US labor market in recent decades. When computers become cheap and competitive compared to workers, they diffuse more rapidly and become more important in the conventional mechanism of capital-labor substitution. The model can account for recent structural changes with this trend of automation: employment has shifted away from routine occupations and the labor share of income has declined. The model also predicts that recessions accelerate the decline in routine occupations—firms prefer to destroy routine jobs during a downturn, when the opportunity cost of restructuring is low. This acceleration can account for recent cyclical changes of the labor market: routine job losses are concentrated in recessions and the ensuing recoveries are jobless.

The second chapter examines the labor market and electricity in the first half of the 20th century. The 1920s and 1930s witnessed large changes in the US labor market, with a shift away from dexterity-intensive occupations, a productivity speedup, and low job creation. The second chapter asks whether the model of the first chapter, which explained labor market changes since the 1980s with the adoption of computers, can also explain labor market changes in the 1930s with the adoption of electricity. It supports the model's main assumption by empirically testing the model's prediction for the labor share of income. The identification strategy uses a state's initial loading on the technology to generate electricity—hydroelectric power or coal power—as an instrument for changes in the price of electricity. It also uses a newly digitized dataset for the concrete industry from 1929 to 1935 to provide plant-level measures of the labor share of income. Technical progress in electric utilities caused a decrease in the labor share of income of the downstream industry of concrete. This result supports the mechanism in the model, which can in turn explain other features of the 1920s and 1930s: structural changes in employment, a productivity speedup, and a weak recovery of employment after the Great Depression.

The third chapter examines the behavior of consumption in the second half of the 20th century. The recoveries from the last three recessions in the United States were not only jobless, they were also slow. The growth rate of output and consumption after the trough of the business cycle is twice as small for the last three recessions compared to previous ones. This chapter asks whether the structural decline in employment of routine occupations can also account for recent slow recoveries in consumption. It assumes that workers in nonroutine occupations are optimizing agents who can smooth consumption by saving, whereas workers in routine occupations are hand-to-mouth agents who consume all of their income. Before the 1980s, workers in routine occupations can easily find another routine job right after the recession, so consumption decreases in the recession and "bounces back" in the recovery. After the 1980s, workers in routine occupations need to go through a period of retraining in order to find a new job, so the recovery of consumption is delayed until they finish retraining. In a simulation of the model, the recovery of consumption is twice smaller after the 1980s than before, which suggests that this mechanism may be quantitatively important in explaining recent slow recoveries.

Contents

List of Tables

List of Figures

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To Madeleine

Chapter 1

Computer adoption and the changing labor market

1.1 Introduction

The US labor market has undergone three structural changes since the 1980s. First, employment has shifted away from routine occupations since 1990. Routine occupations are middle-skill, repetitive jobs that follow explicit rules and are easily automated, such as clerks, accountants, and auditors. Nonroutine occupations are jobs intensive in creativity and personal interactions at both ends of the skill distribution: high-skill cognitive jobs, such as managers and engineers, and low-skill manual jobs, such as janitors and health aides.[1] Second, the growth rate of labor productivity increased from 1.6% before 1995 to 2.5% after 1995.[2] Third, the labor share of income declined by 7.5% between 1981 and

[1]See Autor, Katz and Kearney (2006); Goos and Manning (2007); Goldin and Katz (2007); Autor and Dorn (2009) and Autor (2010).

[2]See Jones (2011).

2007.[3] Several authors suggested computers,[4] whose share of fixed investment accelerated in the 1980s (see Appendix A.4), as a plausible explanation for these changes.

The US labor market has also undergone two cyclical changes since the 1980s: the secular decline in routine jobs is concentrated in recessions,[5] and the ensuing recoveries have been jobless, i.e. employment recovers much slower than output (see Figure 1.1).[6]

This chapter provides a theoretical contribution with a simple model of capital-labor substitution that reconciles the five facts. This chapter bridges the gap between growth and business cycles, between the literature on long-term technology adoption and the literature on the "cleansing effects" of recessions.[7]

The model has two main assumptions relevant for the medium-term behavior of the economy: computer capital substitutes routine jobs more than nonroutine jobs and the price of computer capital decreases with time. Firms producing output with either routine jobs or computer capital adjust their input mix, substituting away from the expensive input of labor and into the cheaper input of capital. The lower demand for routine jobs implies a shift away from these occupations—an endogenous routinization of production. Employment reallocates into nonroutine jobs with high marginal productivity and away from routine jobs with low marginal productivity, so the growth rate of labor productivity increases by a compositional effect—an endogenous productivity speedup. Capital-labor substitution raises payments to capital and reduces those to labor—an endogenous fall in the labor share of income.

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[3]See Blanchard, Nordhaus and Phelps (1997), and Rodriguez and Jayadev (2013).

[4]See Autor, Levy and Murnane (2003); Oliner, Sichel and Stiroh (2007); Brynjolfsson and Hitt (1994); Basu, Fernald and Shapiro (2001); Jorgenson (2001); Karabarbounis and Neiman (2013) and Saint-Paul and Bentolila (2003).

[5]Jaimovich and Siu (2012) find that 95% of the secular decline in routine jobs occurs in recessions.

[6]See Gordon (1993); Andolfatto and MacDonald (2004); and Schreft, Singh and Hodgson (2005).

[7]See Helpman and Trajtenberg (1994); Bresnahan and Trajtenberg (1995); Caballero and Hammour (1994); Aghion and Saint-Paul (1998).

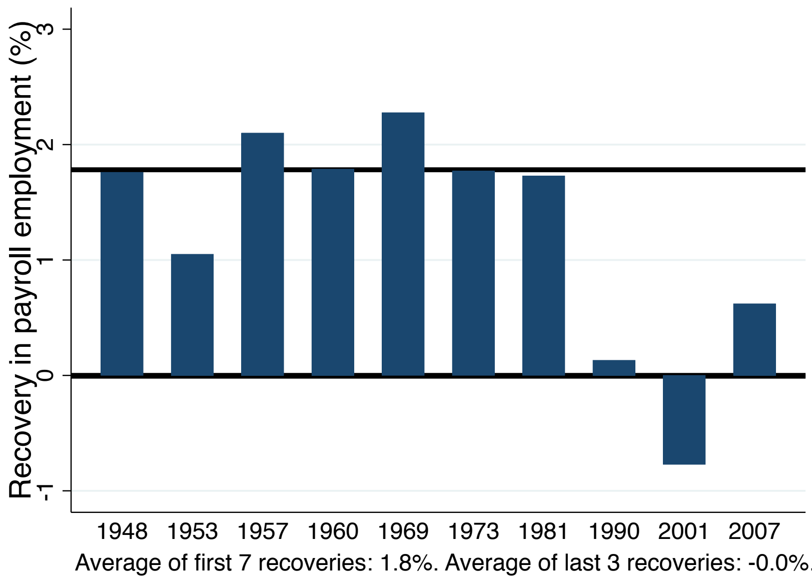


Figure 1.1: Payroll employment is slower to recover after the last three recessions, for a given recovery of output of 5%.

Source: Federal Reserve Economic Database (series PAYEMS and GDPC1). The recovery of employment is $\log(L_{\tau'}/L_{\tau})$, between the NBER trough τ and the time when output recovers by 5%, $\log(Y_{\tau'}/Y_{\tau})$, with linear interpolation.

The model also clarifies why the price of computers has been falling since 1950 but starts affecting the labor market in the 1980s. When computers are too expensive, as in the 1950s, firms use routine jobs instead. Firms always adjust to the change in the price of computers, but the adjustment is small when computers are expensive. Conversely, when computers are cheap, firms have already replaced routine jobs and a further decrease in the price of computers is irrelevant for capital-labor substitution. The substitution of technology capital for labor in routine jobs is quantitatively important when the price of the technology is in a specific range.

The model also clarifies that the substitutability between computer capital and routine jobs needs to be high enough in order to match the structural changes. For example, with a Cobb-Douglas production function, computer capital is equally substitutable to all factors and the routine share of employment is constant. Employment does not reallocate away from routine and into nonroutine, so the growth rate of labor productivity is also constant. The Cobb-Douglas case implies constant factor shares, so the labor share of income is also constant.

To examine the cyclical behavior of the model, the third and last assumption is a hiring cost. In the technological upgrading from routine jobs to computer capital, firms know that they will fire workers in routine occupations in the medium-term. As computers complement nonroutine jobs, firms also know that they will hire more workers in nonroutine occupations. In a recession, forward-looking firms consider how to adjust the two types of jobs. If firms fire workers in nonroutine occupations, they will need to hire them back and pay a hiring cost. So firms avoid destroying nonroutine jobs and hoard them during the recession. In contrast, firing workers in routine occupations does not entail future hiring costs since their medium-term trend is declining. The burden of adjustment falls on routine occupations, whose job losses become concentrated in recessions.

Finally, the model can also account for jobless recoveries. As firms avoid firing workers in nonroutine jobs during recessions, they also refrain from hiring them back temporarily, i.e. they dishoard nonroutine jobs during the recovery. Firms also refrain from hiring workers in routine jobs because of their secular decline. Employment is stagnant even as output recovers, leading to a jobless recovery. When computers are expensive earlier in time, the trend of routine jobs is constant and employment recovers to the pre-crisis level, leading to a "jobful" recovery. A calibration of the model to fit the path of US GDP matches both the structural and the cyclical changes of the US labor market.

Related literature. This chapter relates to two strands of the literature: short-term adjustments of the labor market and General Purpose Technologies. On the short-term adjustments of the labor market, the closest paper is Jaimovich and Siu (2012), which also uses a distinction between routine and nonroutine jobs to explain the concentration of routine job losses in recessions and jobless recoveries. They assume that the productivity of nonroutine jobs increases exogenously faster than the productivity of routine jobs, so workers in routine jobs have an incentive to reallocate into nonroutine jobs. Because of a period of retraining from routine to nonroutine occupations, workers prefer to reallocate when the opportunity cost is low, i.e. during recessions if wages are procyclical. Compared to the labor supply mechanism of Jaimovich and Siu, the model in this chapter uses a labor demand mechanism with hiring costs for firms. Furthermore, the model in this chapter is more robust to the possibility of rigid wages. The cyclical mechanism in Jaimovich and Siu requires wages to fall in recessions, which is counterfactual. This chapter has a baseline model where wages also fall in recessions but it is easy to extend the model to include nominal rigidities. This extension produces similar results: with rigid wages and hiring costs, firms still hoard expanding nonroutine jobs in the recession and shift the burden of adjustment on routine jobs (see Appendix A.5). A second explanation for recent cyclical changes of the labor market is Berger (2012), who argues that the recent decrease in unionization allows firms to fire unproductive workers more easily during the last three recessions. Similar to this chapter, Berger matches the emergence of longer jobless recoveries after the 1980s by distinguishing between two types of workers. A contribution of the model in this chapter is the emergence of jobless recoveries with a continuous mechanism rather than a structural break. Another contribution is to suggest jobless recoveries as a recurrent issue in economic history, linked to the decrease in the cost of an essential input, such as electricity in the 1930s.

Second, the literature on General Purpose Technologies defined them with three characteristics: pervasive use in industry, decreasing cost for a given quality, and capacity to foster other innovations (Jovanovic and Rousseau, 2005, page 1185). If the General Purpose Technology is more substitutable to unskilled labor than to skilled labor, its adoption would increase the skill premium (Jovanovic and Rousseau, 2005, page 1205). This chapter departs from the literature by studying the effects of the General Purpose Technology on the labor share of income rather than on inequality.

1.2 A model of growth and business cycles

This section introduces a model to study the labor market consequences of computer adoption. The model uses computers for clarity but it can also apply to other General Purpose Technologies, such as electricity in the second chapter. Time is indexed as $t = 1, 2, \ldots$. All agents have perfect foresight.

1.2.1 The household

A representative household consumes output, supplies labor, invests in capital, and rents the capital stock. It maximizes utility from consumption, net of disutility from labor supply:

$$\max \sum_{t=0}^{\infty} \theta^t \log\left(C_t - X_t \frac{\varepsilon}{1+\varepsilon} L_t^{\frac{1+\varepsilon}{\varepsilon}} \right), \tag{1.2.1}$$

where θ is the discount factor, X_t is a labor supply shifter, and the remaining notation is standard.[8] The household has preferences as in Greenwood, Hercowitz and Huffman (1988) with no income effects on labor supply.[9] The labor supply shifter X_t has trend growth to ensure a balanced growth path with a constant trend of employment. It can also have a cycle to represent a reduced-form labor wedge.[10]

Capital is either computer capital $K_{C,t}$ or non-computer capital $K_{NC,t}$. The household

[8] Specifically, C_t is consumption, ε is the Frisch elasticity of labor supply, and L_t is labor supply.

[9] See Jaimovich and Rebelo (2009) and Schmitt-Grohe and Uribe (2012) who find small income effects on labor supply in the short-term.

[10] See Hall (1997, page 226) for a similar example of using a preference shifter as a labor wedge. See also Balleer (2012) for the importance of the labor wedge for explaining labor market dynamics.

accumulates capital with a perpetual inventory formula for each type of capital:

$$K_{C,t+1} = (1 - \delta_C)\, K_{C,t} + I_{C,t}, \tag{1.2.2}$$

$$K_{NC,t+1} = (1 - \delta_{NC})\, K_{NC,t} + I_{NC,t}. \tag{1.2.3}$$

The household has access to a technology that transforms output into investment: one unit of output becomes one unit of non-computer investment $I_{NC,t}$ and one unit of output becomes e^{b_t} units of computer investment $I_{C,t}$. Alternatively, the cost of non-computer investment is 1 and the cost of computer investment is e^{-b_t}.

Considering consumption as the numeraire, the household has a budget constraint that balances consumption and investment with labor income and capital income:

$$C_t + I_{NC,t} + \exp(-b_t)\, I_{C,t} = w_t L_t + r_{NC,t} K_{NC,t} + r_{C,t} K_{C,t} + \text{profits}_t, \tag{1.2.4}$$

where w_t is the wage, $r_{J,t}$ are the rental rates of capital ($J = I, N$), and profits_t are the firm's profits in period t, which the household takes as given.

The first crucial assumption is the medium-term increase in the productivity b_t:

Assumption 1. *The logarithm b_t of the productivity of the computer-producing technology increases exogenously with time:*

$$b_t \nearrow \text{ in } t.$$

Alternatively, the cost of computers e^{-b_t} decreases with time. Scholars disagree on the exact rate of decrease in the cost of computers,[11] but agree that it was high. Table 1.1 shows four estimates of the rate of decrease in the cost of computers, ranging from 8 percent to 27 percent. Figure 1.2, from the Bureau of Economic Analysis (BEA), illustrates this rapid decrease: between 1960 and 2010, the cost of computers declined ten-thousand-fold.

[11] See Nordhaus (2007, Table 10, page 153) for a compilation of studies and methods.

Study	Time span	Rate of decrease
Sichel (1997, page 122)	1987-1993	8 %
Bureau of Economic Analysis	1957-2010	18 %
Nordhaus (2007, page 142)	1850-2006	19 %
Berndt and Rappaport (2001, page 271)	1976-1999	27 %

Table 1.1: The cost of computing power decreased significantly over the second half of the 20th century.

1.2.2 Technology

The production function uses four inputs, two types of capital, computer capital $K_{C,t}$ and non-computer capital $K_{NC,t}$, and two types of labor, labor in routine jobs $L_{R,t}$ and labor in nonroutine jobs $L_{NR,t}$. The production function is:

$$Y_t = A_t \, K_{NC,t}^{\alpha} \, L_{NR,t}^{\beta} \, M_t^{\gamma},$$
$$M_t = \left(K_{C,t}^{\frac{\sigma-1}{\sigma}} + L_{R,t}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{1.2.5}$$

where A_t is Total Factor Productivity (TFP) and represents fluctuations driven by technology. The production function has constant returns to scale, with $\alpha + \beta + \gamma = 1$. This production function has Cobb-Douglas aggregation of three factors: non-computer capital $K_{NC,t}$, labor in nonroutine jobs $L_{NR,t}$, and a third factor M_t, which is a Constant-Elasticity-of-Substitution aggregation between computer capital $K_{C,t}$ and labor in routine jobs $L_{R,t}$.

Krusell et al. (2000) use this production function to explain the increase in income inequality with capital-skill complementarity, whereby an increase in capital investment contributes to increasing the skill premium by increasing the marginal product of skilled labor faster than that of unskilled labor. Autor and Dorn (2009, page 11) also use this function to explain the recent disappearance of middle-skill, routine occupations: as firms invest more in computer capital, they increase employment of middle-skill routine jobs

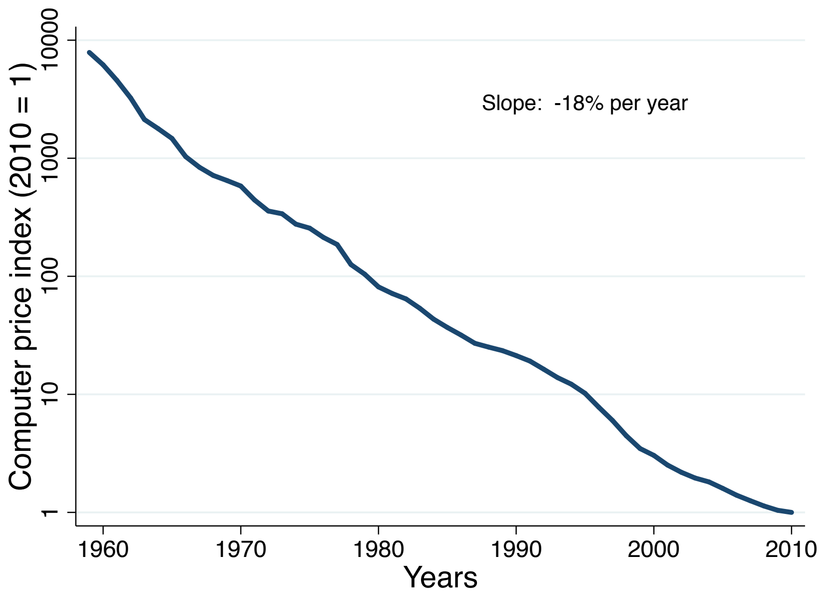


Figure 1.2: The cost of computers has an exponential decrease since 1960.
Source: Bureau of Economic Analysis, Price Indexes for Private Fixed Investment in Equipment by Type (Table 5.5.4U), line "Computers and peripheral equipment."

slower than low-skill or high-skill nonroutine jobs.

The second crucial assumption is the gross substitutability of computer capital and labor in routine jobs:

Assumption 2. *The elasticity of substitution between computer capital and labor in routine jobs is at least greater than 1:*

$$\sigma \geq 1.$$

Autor, Levy and Murnane (2003) find that computer investment is correlated with a decrease in routine jobs and an increase in nonroutine jobs. The case $\sigma > 1$ captures that difference: the elasticity of substitution between routine jobs and computers is greater than the elasticity of substitution between nonroutine jobs and the Constant-Elasticity-of-Substitution aggregate of computers and routine jobs.[12] Intuitively, a computer can

[12]This assumption is both a relative statement, with computers being more substitutable to routine jobs than to nonroutine jobs, and an absolute statement, with the elasticity of substitution between routine

more easily replace automated occupations, such as bank tellers or cashiers, than nonroutine occupations, such as managers and engineers. The possibility of $\sigma = 1$ is kept as a benchmark.

As will become clear in the next section, that computer capital has a decreasing price and is labor-saving implies that computers have two features of General Purpose Technologies: they improve over time and are pervasively used in industry.

1.2.3 The firm

A representative firm demands labor and capital and produces output. It operates under perfect competition and has profits

$$\begin{aligned} \text{profits}_t = {} & Y_t - w_t \left(L_{NR,t} + L_{R,t}\right) - r_{NC,t} K_{NC,t} - r_{C,t} K_{C,t} \\ & - c_{NR} \left(L_{NR,t+1} - L_{NR,t}\right)^+ - c_R \left(L_{R,t+1} - L_{R,t}\right)^+ , \end{aligned} \tag{1.2.6}$$

where $c_J, J = NR, R$ is the unit cost of hiring workers in nonroutine or routine jobs and $x^+ = \max(x, 0)$ is the positive operator. Linear adjustment costs to labor are common in the literature (Bentolila and Saint-Paul, 1994) as opposed to quadratic adjustment costs for capital (Caballero and Hammour, 1994). The firm reverts profits to the household and uses the household's discount factor weighted by marginal utility from consumption to compute the present discounted value of profits (see Appendix A.1).

The third crucial assumption bears on the adjustment cost:

Assumption 3. *The costs of hiring are non-negative:*

$$c_{NR} \geq 0, \qquad c_R \geq 0.$$

jobs and computers being greater than 1.

Hiring costs capture the firm-specific value of a match, such as a training cost paid by the firm for a new worker. This assumption follows from the extensive literature documenting positive hiring costs: Blatter, Muehlemann and Schenker (2012) estimate hiring costs around one quarter of wages using a dataset of Swiss firms, which Del Boca and Rota (1998) confirm using a survey of Italian firms. Hamermesh (1993) reports similar values for the United States: in 1980, the average employer spent 42 hours and two quarters of wages recruiting and training a new hire.[13]

1.2.4 Equilibrium

The clearing of the labor market requires that labor supply equal labor demand:

$$L_t = L_{NR,t} + L_{R,t}. \tag{1.2.7}$$

This condition, in combination with the utility function, implies that the household is indifferent between the two types of jobs. Labor supply is perfectly substitutable between routine and nonroutine occupations and the difference is due to labor demand.[14] This unrealistic assumption distinguishes this model from Jaimovich and Siu, where the difference between routine and nonroutine is entirely due to labor supply. This chapter assesses the contribution of labor demand alone in explaining the structural and cyclical changes of the US labor market.[15]

[13]Assumption 3 implies that hiring costs are larger than firing costs, which is consistent with Hamermesh: "The [1965] study found separation costs to be much smaller, roughly $1,780." For simplicity, the model assumes that firing costs are zero.

[14]The clearing of the labor market implies that the wage is endogenous in the model and equates demand and supply.

[15]With costly reallocation between the two types of labor, the wage for routine jobs is lower than that for nonroutine jobs and workers in routine occupations remain competitive for a longer period of time, which would attenuate the medium-term effects of the model. In contrast, this costly reallocation would strengthen the short-term effects of the model by a mechanism similar to Jaimovich and Siu: the wage is the opportunity cost of reallocation and workers prefer to switch jobs during a recession.

The clearing of the product market follows from the budget constraint, the definition of the firm's profits, and the clearing of the labor market. The clearing of the capital market is implicit in the use of a single symbol for capital supply and capital demand.

An equilibrium of this economy is a set of quantities (consumption C_t, investments $I_{C,t}$ and $I_{NC,t}$, capital stocks $K_{C,t}$ and $K_{NC,t}$, employment quantities L_t, $L_{NR,t}$ and $L_{R,t}$, and output Y_t) and prices (rental rates $r_{C,t}$ and $r_{NC,t}$, and wages w_t), conditional on exogenous variables (TFP A_t, the productivity b_t of the computer-producing technology, and the labor supply shifter X_t), such that the household maximizes utility (1.2.1) subject to the capital accumulation constraints (1.2.2-1.2.3) and the budget constraint (1.2.4); the firm maximizes the present discounted value of profits (1.2.6) subject to the production function (1.2.5); and all markets clear. This model nests the Ramsey growth model, which corresponds to a two-factor production function ($\gamma = 0$), no adjustment costs ($c_{NR} = c_R = 0$), and constant labor supply.

The full characterization of the model is in Appendix A.1. An equilibrium of this model exists as long as the labor supply of the household is bounded above (see Appendix A.1 for the proof using the contraction mapping theorem). This assumption is used only in the theoretical setting and never binds numerically.

Lemma 4. *If the labor supply of the household is bounded above, $L_t \leq \bar{L}$, an equilibrium exists and it is unique.*

1.2.5 Balanced growth path

The model has an asymptotic balanced growth path, consistent with the "Kaldor facts" of a constant interest rate and a constant capital-output ratio (Kaldor, 1961). The following lemma characterizes the behavior of the asymptotic balanced growth path, where employment is constant and all other quantities, aside from employment, grow at the same rate.

Lemma 5. *Consider the limiting economy, where TFP grows at rate* $g_A > 0$*,* b_t *tends to* $\bar{b}$*, the marginal utility from consumption declines at rate* g_μ*, the capital stocks grow at rate* $g_{K_{NC}}$ *and* g_{K_C}*, and the labor supply shifter grows at rate* $g_X = g_A/\beta$*. Then employment is constant and consumption, output, and all quantities other than employment grow at rate* g_A/β*.*

This model is analytically intractable and has no closed-form solution. The next section examines a simplified version of the model that has a closed-form solution to clarify the conditions to match the structural changes of the labor market. Section 1.4 uses the general version of the model to examine the cyclical changes.

1.3 Medium-term trends

The general model combines growth and business cycles to understand the interaction between the trend of routinization and the recession. As a first step in understanding the model, this section uses a simplified version to clarify under which conditions capital-labor substitution leads to the routinization of production, to a productivity speed-up, and to a decline in the labor share of income.

1.3.1 Simplifications

Two simplifications render the model analytically tractable. First, hiring costs are zero, with $c_{NR} = c_R = 0$, so the firm is free to adjust labor. Second, capital accumulates immediately and depreciates fully after one period:

$$K_{NC,t} = I_{NC,t},$$

$$K_{C,t} = I_{C,t}.$$

The firm has no frictions and makes zero profits in all periods. Since capital equals investment, the household's budget constraint in equation (1.2.4) is

$$C_t + (1 - r_{NC,t}) K_{NC,t} + (\exp(-b_t) - r_{C,t}) K_{C,t} \leq w_t L_t.$$

In equilibrium, the household sells capital to the firm at marginal cost, with $r_{NC,t} = 1$ and $r_{C,t} = \exp(-b_t)$, and the budget constraint becomes

$$C_t = w_t L_t.$$

The household cannot smooth consumption and the intertemporal utility maximization is equivalent to a set of independent maximization programs, one for every period. The household behaves as if it were infinitely impatient, with $\theta \to 0$, or as if it lived for one period and a new household made decisions in the next period.

1.3.2 Endogenous structural changes

This subsection describes how Assumptions 1 and 2, with the restriction $\sigma > 1$, match the three structural changes of the labor market. In contrast, the Cobb-Douglas case $\sigma = 1$ cannot match those changes. This subsection considers constant TFP, with $A_t = A$. The time-varying exogenous variables are the labor supply shifter X_t and the productivity b_t of the computer-producing technology.

Full depreciation of capital pins down the rental rates of capital as the prices of investment. The missing price in the economy is the wage, which follows from the factor price frontier in the next lemma. (See Appendix A.3 for all proofs in this subsection.)

Lemma 6. *For $\sigma > 1$, the wage is the unique solution to the factor price frontier:*

$$1 = \frac{1}{A_t} \left(\frac{1}{\alpha}\right)^{\alpha} \left(\frac{w_t}{\beta}\right)^{\beta} \left(\frac{\left(r_{C,t}^{1-\sigma} + w_t^{1-\sigma}\right)^{\frac{1}{1-\sigma}}}{\gamma}\right)^{\gamma}. \tag{1.3.1}$$

The left-hand side of the factor price frontier is the marginal benefit of selling one more unit of output, whose price is normalized to 1. The right-hand side is the marginal cost: the inverse of Total Factor Productivity multiplied by the marginal price of each Cobb-Douglas factor divided by its share and raised to that share. The marginal price of non-computer investment is 1, the marginal price of nonroutine jobs is the wage w_t, and the marginal price of the third factor is a Constant-Elasticity-of-Substitution aggregation between the rental rate of computer capital and the wage.

The aggregation between the rental rate of computers and the wage is the key to the model's ability to match the structural changes. To understand the economic intuition for this mechanism, consider the two limits of expensive and cheap computers. When computers are expensive, the term $r_{C,t}^{1-\sigma}$ vanishes from the equation and the factor price frontier is close to that of a labor-intensive production function with three Cobb-Douglas factors of non-computer capital, labor in nonroutine occupations, and labor in routine occupations:

$$\lim_{b_t \to -\infty} Y_t = A_t \, K_{NC,t}^{\alpha} \, L_{NR,t}^{\beta} \, L_{R,t}^{\gamma}.$$

When computers are cheap, the term $r_{C,t}^{1-\sigma}$ gains importance, the term $w_t^{1-\sigma}$ vanishes from the equation, and the factor price frontier is close to that of a capital-intensive production function with three Cobb-Douglas factors of in non-computer capital, labor in nonroutine occupations, and computer capital:

$$\lim_{b_t \to \infty} Y_t = A_t K_{NC,t}^{\alpha} L_{NR,t}^{\beta} K_{C,t}^{\gamma}.$$

The transition from expensive to cheap computers is a phase of technological upgrading from a labor-intensive to a capital-intensive production function. The transition phase matches the three structural changes of the US labor market. Employment shifts away from routine jobs, which have a share of γ in the labor-intensive production function and a share of 0 in the capital-intensive production function. Computers do not contribute to output and labor productivity in the labor-intensive production function but they do contribute in the capital-intensive production function, so labor productivity speeds up. The labor share of income decreases from $\beta + \gamma$ in the labor-intensive production function to β in the capital-intensive production function.

Even though computers are steadily becoming cheaper, they do not affect the economy in the region of the labor-intensive production function. The price of computers has been decreasing since 1950, but at the time they were so expensive that firms relied on routine jobs instead. It is in the 1980s that computers become competitive compared to routine jobs and start affecting the economy. The firm always adjusts to the change in the price of computers but the adjustment is small when the cost of computers is large.

The rest of this section supports this economic intuition. It shows analytically that $\sigma > 1$ and an increase in b_t are sufficient for the model to match the structural changes of the US labor market. It also shows that, when the price of computers is sufficiently high, a decrease in the price of computers has little effect on the economy.

The next proposition shows that a decrease in the cost of computers causes a decrease in the routine share of employment. An increase in productivity b_t makes computer capital cheaper and impacts routine jobs more than nonroutine jobs. Given the single labor market, the household reallocates away from routine jobs and into nonroutine jobs. This prediction is consistent with the routinization hypothesis of Autor, Levy and Murnane (2003), who find that the use of computers decreases demand for routine jobs.

Proposition 7. *For $\sigma > 1$, the routine share of employment decreases:*

$$\lim_{b_t \to -\infty} \frac{L_{R,t}}{L_t} = \frac{\gamma}{\beta + \gamma}, \qquad \lim_{b_t \to \infty} \frac{L_{R,t}}{L_t} = 0.$$

Moreover, the productivity b_t of the computer-producing sector impacts the logarithm of the routine share of employment, $s_t = \log(L_{R,t}/L_t)$, with increasing importance:

$$\lim_{b_t \to -\infty} \frac{\partial s_t}{\partial b_t} = 0, \qquad \lim_{b_t \to \infty} \frac{\partial s_t}{\partial b_t} = (1 - \sigma)\left(1 + \frac{\gamma}{\beta}\right).$$

The next proposition shows that progress in the computer-producing technology causes a productivity speedup in the wider economy.

Proposition 8. *For $\sigma > 1$, the variable b_t impacts labor productivity $\pi_t \equiv \log Y_t/L_t$ with increasing importance:*

$$\lim_{b_t \to -\infty} \frac{\partial \pi_t}{\partial b_t} = 0, \qquad \lim_{b_t \to \infty} \frac{\partial \pi_t}{\partial b_t} = \frac{\gamma}{\beta}.$$

For $\sigma \in (1, 2]$, the effect of b_t on labor productivity is monotonic, i.e. labor productivity is log-convex in b_t:

$$\frac{\partial^2 \pi_t}{\partial b_t^2} > 0.$$

For $\sigma > 2$, the effect of b_t on labor productivity has an inflexion point:

$$\frac{\partial^2 \pi_t}{\partial b_t^2} > 0 \quad \textit{iff } b_t < b^*.$$

The transition between the two asymptotes for labor productivity can be monotonic, for $\sigma \leq 2$, or non-monotonic, for $\sigma > 2$. To understand the inflexion point, consider the extreme case of $\sigma = +\infty$. Then computers are infinitely substitutable with routine occupations and the cost of computers has a threshold at $r_{C,t} = w_t$, when the firm fires all routine occupations and invests in computer capital. The technological upgrading phase is instantaneous: the growth rate of labor productivity is zero before the threshold (since TFP is constant), infinite at the threshold, and finite after the threshold. For finite σ, the effects of b_t on labor productivity are continuous with no threshold. When computers and routine occupations are substitutable enough, i.e. for $\sigma > 2$, the behavior of productivity also has an inflexion point, with a rapid replacement of workers with computers for $b_t \leq b^*$. For moderate substitution between computers and computers, for $1 < \sigma \leq 2$, the behavior of productivity between the two asymptotes is smooth and monotonic. The threshold of $\sigma = 2$ is similar to Acemoglu (2009, page 510), who finds a different behavior for an economy with directed technical change depending on whether the elasticity of substitution between skilled and unskilled labor is above or below 2.

Another interpretation of log-convex labor productivity is that the impact of technological progress of the computer-producing sector on the wider economy is increasing with time. The impact factor is the ratio of $\dot{\pi}_t/\dot{b}_t$, which equals $\dot{b}_t\, \partial^2\pi_t/\partial b_t^2$ and is increasing with time for $\sigma \in (1, 2]$.

The next proposition shows that a decrease in the price of computers causes a decrease in the labor share of income.

Proposition 9. *For $\sigma > 1$, the labor share of income decreases from $\beta + \gamma$ to β, linked to the relative price of computer capital:*

$$\frac{w_t L_t}{Y_t} = \beta + \gamma \left(1 + \left(\frac{r_{C,t}}{w_t} \right)^{1-\sigma} \right)^{-1} \searrow \text{ in } t,$$

$$\lim_{b_t \to -\infty} \frac{w_t L_t}{Y_t} = \beta + \gamma, \qquad \lim_{b_t \to \infty} \frac{w_t L_t}{Y_t} = \beta.$$

To understand the relevance of the assumption of substitutability between computers and routine occupations with $\sigma > 1$, consider the limit of $\sigma \to 1$. The next corollary shows the absence of differential effects from the price of computers: productivity growth, the labor share of income, and the routine share of employment are constant. At the limit $\sigma \to 1$, the production function tends to a four-factor Cobb-Douglas aggregation of non-computer capital, labor in nonroutine occupations, computer capital, and labor in routine occupations. Computer capital is equally substitutable to all factors and the routine share of employment is constant. Employment does not reallocate away from routine and into nonroutine, so the growth rate of labor productivity is also constant. The Cobb-Douglas case implies constant factor shares, so the labor share of income is also constant.

Corollary 10. *If $\sigma \to 1$, the effect of computers on labor productivity, the labor share of income, and the routine share of employment are independent of computer productivity:*

$$\left.\frac{\partial s_t}{\partial b_t}\right|_{\sigma \to 1} = \left.\frac{\partial^2 \pi_t}{\partial b_t^2}\right|_{\sigma \to 1} = \left.\frac{\partial \log (w_t L_t / Y_t)}{\partial b_t}\right|_{\sigma \to 1} = 0.$$

Therefore the two assumptions of $\sigma > 1$ and an increase in b_t are required to match the three structural changes of the US labor market since the 1980s.

1.3.3 Illustration

To illustrate the mechanism numerically, this subsection calibrates the crucial parameters, with the remaining parameters calibrated in the full model in Section 1.4. The two important parameters are the path of b_t and the elasticity of substitution σ. With an exponential decrease in the cost of computers and $\sigma > 1$, the model matches the structural changes. The calibration uses a cost of computers that decreases at rate $\phi = 18\%$ per year, the estimate from the Bureau of Economic Analysis in the middle range of Table 1.1.

The value of σ relates to a substantial literature on the estimation of the elasticity of substitution between aggregate capital and aggregate labor. Using cross-country variation in the price of investment, Karabarbounis and Neiman (2013) estimate the elasticity of substitution at 1.25. Accounting for technological change that may be biased toward some factors, Antràs (2004) estimates elasticities of substitution that are not statistically different from 1. Unlike the previous literature that mostly focused on the elasticity of substitution between aggregate capital and aggregate labor, Krusell et al. (2000) estimate the elasticity of substitution between unskilled labor and equipment. Using time-series data for the United States, they find an elasticity of substitution of 1.67. Given that this estimate is closest in spirit to the elasticity of substitution between computer capital and routine jobs, this chapter uses $\sigma = 1.67$. Further support for this value comes from the calibration of the general case of the model in the next section, which predicts a decline in the labor share of income that is similar to that in the data (see Figure A.3 in the Appendix).

Figure 1.3 shows the behavior of the economy in the medium-term with fictional dates. Total Factor Productivity is constant, with $A_t = A$. The labor supply shifter X_t grows and exactly offsets the increase in the wage so the economy has constant employment, as in the balanced growth path of Lemma 5. Early in time, the productivity of the computer-producing technology is low and it has a minimal effect on routine jobs, labor productivity, and the labor share. Intuitively, computers are too expensive and the firm relies on routine jobs instead. The labor-intensive phase lasts roughly until the 1980s in this example and is characterized by near zero share of computer capital in total capital, a constant routine share of employment, a constant growth rate of labor productivity, and a constant labor share of income.

As the cost of computers decreases, they become a more attractive investment and the firm starts replacing routine occupations with computers. Labor reallocates away from routine jobs L_R and into nonroutine jobs L_{NR}, away from jobs that are easily replaced by computers and into jobs that are more difficult to replace with computers. The marginal product of nonroutine jobs is higher than the marginal product of routine jobs, so labor productivity increases by a compositional effect. The firm's expenses shift away from routine jobs and into computer capital, so the labor share of income falls. The economy

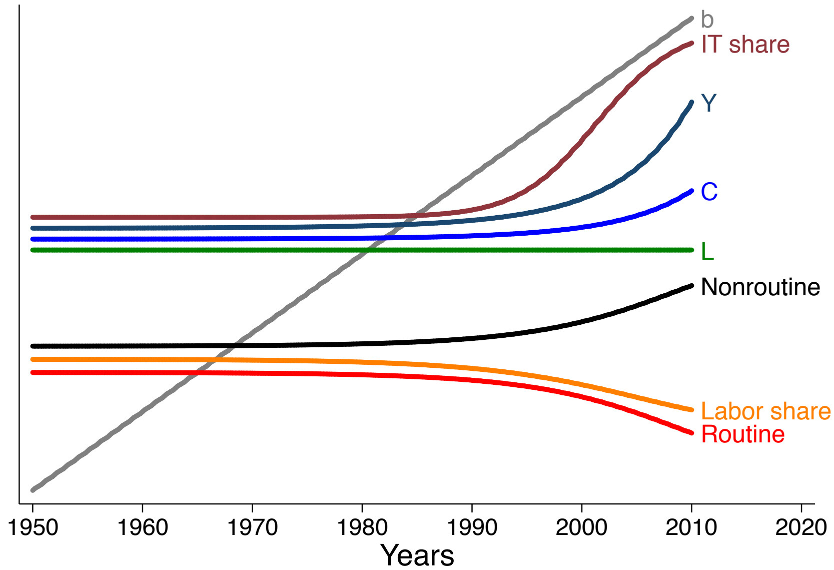


Figure 1.3: The special case of the model matches the medium-term changes: a linear increase in the productivity of the computer-producing sector causes a decline in the routine share of employment, a speedup in labor productivity, and a fall in the labor share of income.

is in a technological upgrading phase, characterized by an increasing stock of computer capital. As mentioned earlier, the transition between the two phases is continuous and has no threshold effects: the firm always adjusts its input mix, but the adjustment is quantitatively small when the cost of computers is large.

1.3.4 From medium-term to short-term

This subsection clarifies the link between the productivity speedup in the medium-term and jobless recoveries in the short-term both analytically and numerically. Note first that labor productivity depends on the wage and on the cost of computers (see Proposition 9), and the wage depends on the cost of computers and TFP. So labor productivity is independent of the labor supply shifter X_t and has only has a trend, due to the increase in the productivity of the computer-producing technology. The next proposition links the medium-term productivity speedup to jobless recoveries.

Proposition 11. *Suppose that Total Factor Productivity is constant ($A_t = A$), that the trend component of the labor supply shifter X_t offsets the growth in wages, and that the cyclical component of X_t is periodic, with a single trough in each cycle. Define the length of the jobless recovery as the difference between the trough of output and the trough of labor. If the length of the jobless recovery is small compared to the period of the business cycle, the theoretical first-order effect of a productivity speedup is to cause longer jobless recoveries.*

Productivity growth is the difference between output growth and employment growth. The faster the growth rate of labor productivity, the longer output can increase with labor simultaneously decreasing—a jobless recovery. A speedup in labor productivity between the labor-intensive phase and the technological upgrading phase implies that jobless recoveries last longer since the 1980s. This result depends on the two assumptions of an increase in b_t and $\sigma > 1$. In the Cobb-Douglas case with $\sigma = 1$, productivity growth is constant, so productivity growth and the length of jobless recoveries are constant.

The following numerical simulation confirms the accuracy of the first-order approximation. Total Factor Productivity is constant, with $A_t = 1$. The labor supply shifter X_t has a trend component $\bar{X}_t$ which exactly offsets the growth in wages to guarantee that the trend of employment is constant. The labor supply shifter also has a cyclical component $\tilde{x}_t$, which follows an AR(1) process:

$$X_t = \bar{X}_t e^{\tilde{x}_t}, \qquad \tilde{x}_t = 0.8527\, \tilde{x}_{t-1} + 0.0166 \times \mathcal{N}(0, 1).$$

This specification matches the persistence and variance of output implied by the model to those of US GDP.[16]

[16]Real GDP detrended with an HP filter has an auto-correlation at one lag of 0.8527 and a standard deviation of 0.0166. Detrended output in logarithms equals x_t: employment is $L_t = (w_t/X_t)^{1/\epsilon} = e^{-\tilde{x}_t}$ and labor productivity has only a trend and no cycle. Matching the summary statistics of output consists simply of using the same parameters for the cyclical component of the labor supply shifter.

Given these exogenous variables, the model determines the path of the other variables, including output and employment. Define a trough of a quantity when it has two previous quarters of decrease and two succeeding quarters of increase and a jobless recovery when the trough of labor lags the trough of output. The frequency of jobless recoveries is:

$$\mathbb{P}\left(\text{jobless recovery of length } n \text{ at } t\right) = \frac{\#\left\{\text{jobless recoveries of length } n \text{ at } t\right\}}{\#\left\{\text{recoveries at } t\right\}}.$$

Figure 1.4 plots this frequency of jobless recoveries for 100,000 paths of $\tilde{x}_t$: as the cost of Information Technologies decreases, the probability of a jobless recovery is larger and jobless recoveries are longer.

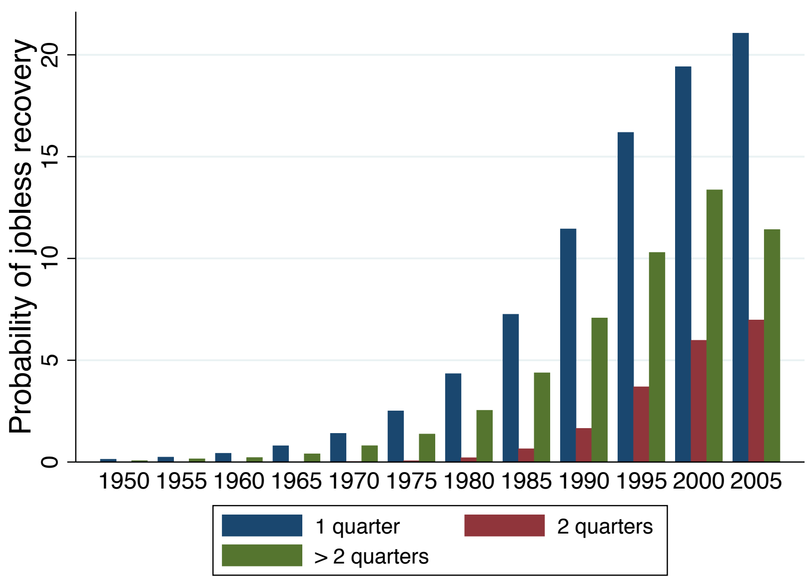


Figure 1.4: The probability of a jobless recovery increases with time.

The special case of the model clarifies the importance of Assumptions 1 and 2 to match the structural changes. It abstracts from business cycles and a recession is simply an upward or downward scaling of all variables. Yet, the literature on the "cleaning effects of recessions," such as Caballero and Hammour (1994) and Aghion and Saint-Paul (1998), suggests that downturns are special times for restructuring production. The next section relaxes the simplifying assumptions and examines the implications of the model in the general case.

1.4 Short-term predictions

This section considers the general version of the model, with positive hiring costs and accumulation of capital. Compared to the special case of the model above, the main difference is the firm's choice of the optimal time to fire workers. Firms know that nonroutine jobs are expanding in the medium-term. Instead of firing workers in nonroutine jobs during recessions and paying a hiring cost in the recovery, firms hoard or retain nonroutine jobs during the recession. In contrast, routine jobs are declining and do not imply hiring costs in the recovery. The burden of adjustment falls on routine jobs. The interaction between hiring costs and the secular decline implies that routine job losses are concentrated in recessions during the technological upgrading phase.

1.4.1 Calibration

The calibration of the model uses the same values for the elasticity σ and the rate of decrease ϕ as Section 1.3.3. The hiring costs are between zero and one quarter of wages initial wages w_{1947}.[17] The share of non-computer capital is $\alpha = 0.3$, the standard share of capital in aggregate income. The nonroutine share $\beta = 0.39$ of aggregate output is from the Current Population Survey in 2007, identifying workers as nonroutine if they are below the median of an index of routinization defined in subsection 1.4.3.[18] The quarterly discount factor is $\theta = 0.99$. The elasticity of labor supply is $\varepsilon = 1$, consistent with Keane (2011,

[17]This value is consistent with previous literature: the adjustment costs in Berger (2012, page 23) are 7 months of wages. In the calibration with US GDP, spending on hiring costs is at most 0.2% of GDP.

[18]Multiplying the nonroutine share of labor income of 56 percent in 2007 by the labor share of income of 70 percent yields $\beta = 0.392$.

page 1042). The depreciation of non-computer capital is $\delta_{NC} = 1.5\%$ and the depreciation of computer capital is $\delta_C = 7.5\%$ (6% and 30% in annual terms). Henceforth, the model considers only TFP shocks. The labor supply shifter has no cyclicality and grows at a rate that ensures a constant trend in employment.

Parameter	α	β	γ	σ	c_{NR}, c_R	θ	ε	δ_C	δ_{NC}
Value	0.3	0.39	0.31	1.67	$0, 0.1,$ or 0.8	0.99	1	7.5%	1.5%

Table 1.2: Parameter values for the calibration of the model.

1.4.2 Acceleration of routinization in simulations

The model is analytically intractable and requires a numerical solution. This subsection illustrates a property of the model with numerical simulations: routine jobs are more responsive to a recession than nonroutine jobs. This subsection uses symmetric hiring costs, with $c_{NR} = c_R = c$.

The behavior of routine jobs during a recession has three parts: a trend component and two cyclical components. The *trend* component corresponds to the secular decline in routine jobs. The *frictionless cyclical* component corresponds to the hypothetical response of routine jobs to the recession in the absence of adjustment costs ($c = 0$). The *frictional cyclical* component corresponds to the additional response of routine jobs to the recession with frictions, e.g. to the response of routine jobs with adjustment costs versus without adjustment costs. The first two components, trend and cycle without frictions, are present in the special case of the model. The third component, cycle with frictions, is due to intertemporal substitution in the firm's behavior.

The specification for TFP shocks follows the standard AR(1) process in Kydland and

Prescott (1982):

$$\log A_t = 0.95 \log A_{t-1} + 0.009 \times \mathcal{N}(0,1).$$

These simulations use a path for TFP with no trend growth. (Note that this calibration of TFP shocks concerns only these simulations, while the fit of US data in the next subsection computes the implied TFP shocks directly from the data.) The simulations use 300 paths for TFP A_t and solve two models, without and with adjustment costs ($c = 0$ or $c = 0.1$). Denote $\left\{L^i_{NR,c_{NR},t}, L^i_{R,c_{NR},t}\right\}$ the solution to path i of the TFP series.

The simulations confirm that the burden of adjustment of a TFP shock falls on routine occupations more than on nonroutine occupations. The elasticity of employment with respect to negative TFP shocks is the coefficient of a regression of $\Delta \log L_{J,c_{NR},t}$ on $\Delta \log A_t$, for $\Delta \log A_t < 0$, $J = NR, R$, and $c = 0, 0.1$. The elasticity of employment with respect to TFP shocks in the technological upgrading phase is also similar without adjustment costs: 0.71 for routine jobs and 0.72 for nonroutine jobs. With symmetric adjustment costs, the elasticity of routine jobs is 0.31, six times higher than the elasticity of nonroutine jobs at 0.05.

1.4.3 Acceleration of routinization in a fit to US GDP

An alternative to the numerical simulations is to fit the model with US GDP. The adjustment costs are $c_{NR} = 0.8$, which correspond to one quarter of wages at the beginning of the period, and $c_R = 0$. The simplifying assumption of zero routine hiring costs implies that no cyclical force holds back the hiring of routine occupations in the recovery.[19]

The growth in the labor supply shifter X_t requires delicate attention. Recent recoveries

[19]Zero routine hiring costs imply that aggregate employment responds to a recession, whereas routine hiring costs with one quarter of wages would prevent firing of workers in routine jobs during early recessions and imply acyclical employment.

are not only jobless but also slow (Galí, Smets and Wouters, 2012): output recovers faster after early recessions than recent ones. For a given recovery in output, recent recoveries last longer. A constant growth in the disutility of labor supply would imply that the household is less willing to work in recent recoveries than in earlier ones, which would bias in favor of jobless recoveries. To remove this labor supply mechanism and decrease the chances of matching jobless recoveries, the calibration specifies a growth rate for X_t of 3.8% before 1985, larger than the growth rate of 1.71% after 1985. Over the whole period, the trend of employment is constant.

The numerical solution computes the shocks to TFP A_t that match US GDP exactly. Specifically, the characterization of the equilibrium in Appendix A.1 gives n equations with $n+1$ unknowns for each time period, the extra unknown being the TFP shock. To pin down the model, the numerical solution uses output as an additional series and obtains n equations in n unknowns. This approach matches output by construction and computes the TFP shocks that are exactly consistent with output. It also avoids computing a nested fixed point and allows an efficient calibration that solves in a few seconds.[20]

This calibration is similar to the growth accounting exercise of imputing the "Solow residuals" as unobserved TFP shocks. In both approaches, the model and the regression fit the path of output perfectly by computing the implied TFP shocks. This calibration is not a test of the model, since the path of output is taken from the data, but illustrates the mechanism of nonroutine hoarding during recent recessions in perfect foresight. Berger (2012) uses a similar approach and computes the path of aggregate-level TFP shocks that are exactly consistent with output during the 2007 recession.

The key mechanism in the model is the differential behavior of routine and nonroutine jobs. Using the calibration with US GDP, Figure 1.5 illustrates this difference in the

[20]See Conlon (2010) for time-efficient solutions of constrained optimization problems using the AMPL software.

calibration of the model over the last four decades. The firm hoards nonroutine occupations during recessions, rather than firing them in a recession and hiring them again in a recovery. This hoarding causes the firm to fire workers in routine occupations more than without nonroutine hoarding. In all the recessions of Figure 1.5, the firm hoards nonroutine jobs and adjusts with routine jobs. In recent decades, a recession accelerates the secular decrease in routine jobs.

Comparing this differential behavior during recent recessions to the data requires the Current Population Survey matched to the Occupational Information Network. For a measure of routinization, Autor, Levy and Murnane (2003) classify routine jobs as high in automation, low in personal interactions, and low in creativity. An index of routinization combines these three measures:

$$\text{routinization}_j = \text{automation}_j - \text{assisting others}_j - \text{level of creativity}_j,$$

where j indexes occupations. I aggregate employment into employment quartiles by routinization index for each peak year, divide employment by working-age population,[21] and normalize the employment share quartiles at 100 in the peak year.

Figure 1.6 is the empirical counterpart of Figure 1.5 and plots the time-series of each quartile by decade.[22] The least routinizable occupations, in the first quartile, represent nonroutine and expanding jobs: they have the largest medium-term increase in all decades and never decrease during recessions. Occupations that are neither routine nor nonroutine, in the second quartile, represent cyclical jobs: they increase during expansions and decrease during recessions. The most routinizable occupations, in the third and fourth quartiles,

[21] I use the series USAWFPNA from the Federal Reserve Economic Database.

[22] The occupational classification of the CPS changed every decade. The 2003-2010 panel uses the 6-digit Standard Occupation Classification of 2000 (SOC2000). The remaining panels use the OCC1990 variable provided by IPUMS.

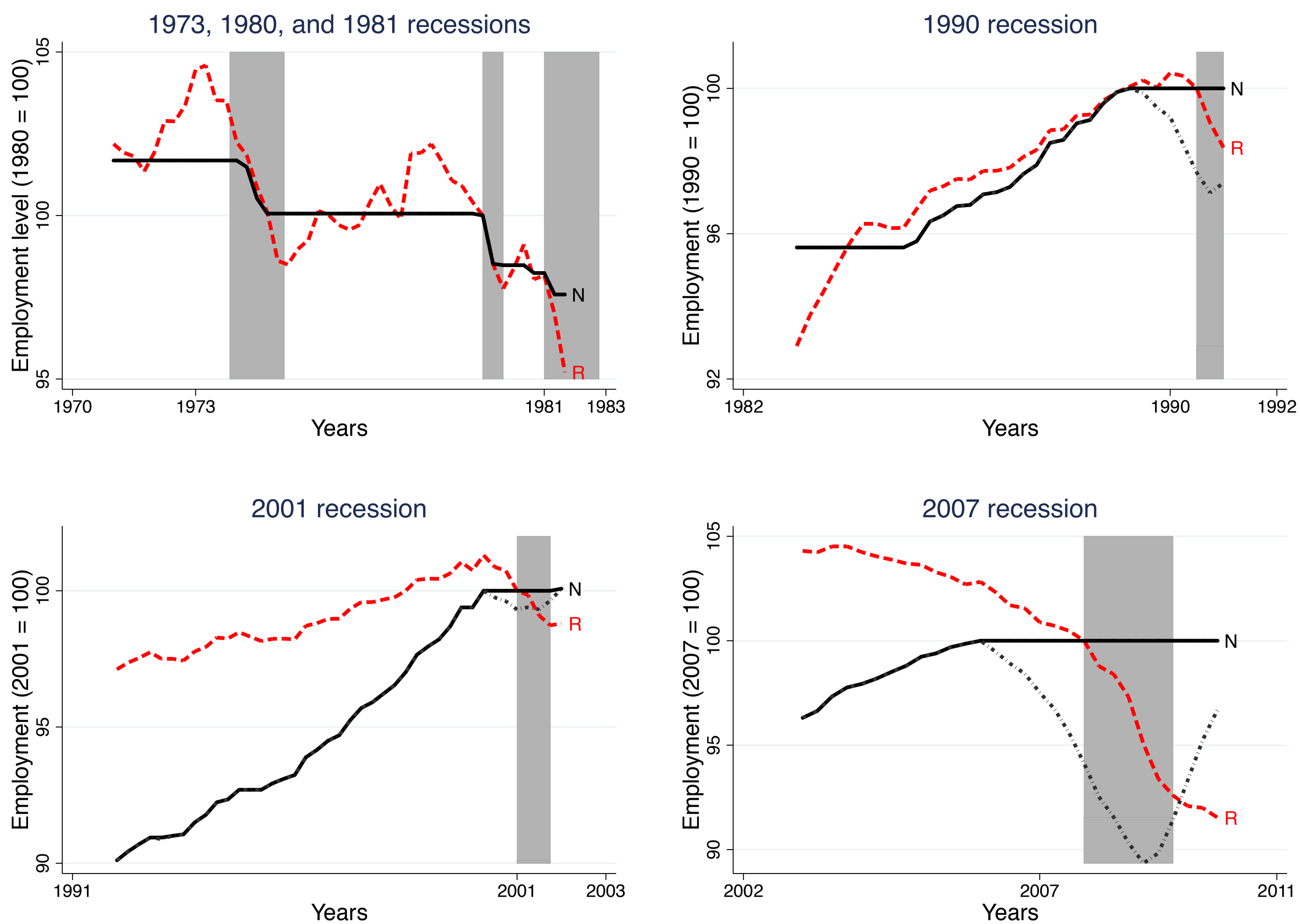


Figure 1.5: The calibration of the model predicts an acceleration of the decline in routine occupations during recent recessions.

Shaded areas are NBER recessions. Nonroutine jobs “N” are the solid black line, routine jobs “R” are the dashed red line, the lower inaction band for nonroutine jobs is the dot-dashed black line. This inaction band is far below employment in nonroutine jobs before 1984 and is omitted for clarity.

represent declining jobs, intensive in automation and with little scope for personal interactions or creativity. Employment in these occupations follows a step function: flat or declining in the 1990 and 2000 expansions and decreasing during recessions. Between 2007 and 2010, employment in upper quartiles of routinization decreased by 5.8 million jobs, around 80% of job losses over the period. For 1990 and 2001, routine occupations also represent around 80% job losses.

1.4.4 Jobless recoveries

The calibration of the model to fit US GDP also matches jobless recoveries. As a consequence of hoarding nonroutine jobs during a recession, the firm dishoards them during the recovery. During the recession, the firm has a stock of nonroutine jobs that is temporarily too high. To return to the ideal allocation that would prevail without adjustment costs, the firm refrains from hiring workers in nonroutine occupations for some time during the recovery. Routine jobs adjust freely: they return to peak in early recoveries and to the declining trend in late recoveries. Routine jobs are V-shaped in early recessions and L-shaped in late recessions. After early recessions, the firm dishoards nonroutine jobs and hires routine jobs back to peak, leading to a "jobful" recovery. After late recessions, the firm also dishoards nonroutine jobs but routine jobs return to their declining trend. Aggregate employment is stagnant even as output recovers, leading to a "jobless" recovery. The jobless recovery lasts until the firm exits the dishoarding regime and starts hiring workers in nonroutine jobs again.

Figure 1.7 shows the recovery of employment in two numerical exercises. The first exercise solves a model without computers, where the productivity b_t of the computer-producing sector is constant at the 1947 level. The second exercise solves a model where the price of computers falls at rate $\phi = 18\%$. Without computers, the average recovery of employment is the same for all recessions. With computers, the recovery of employment drops from an

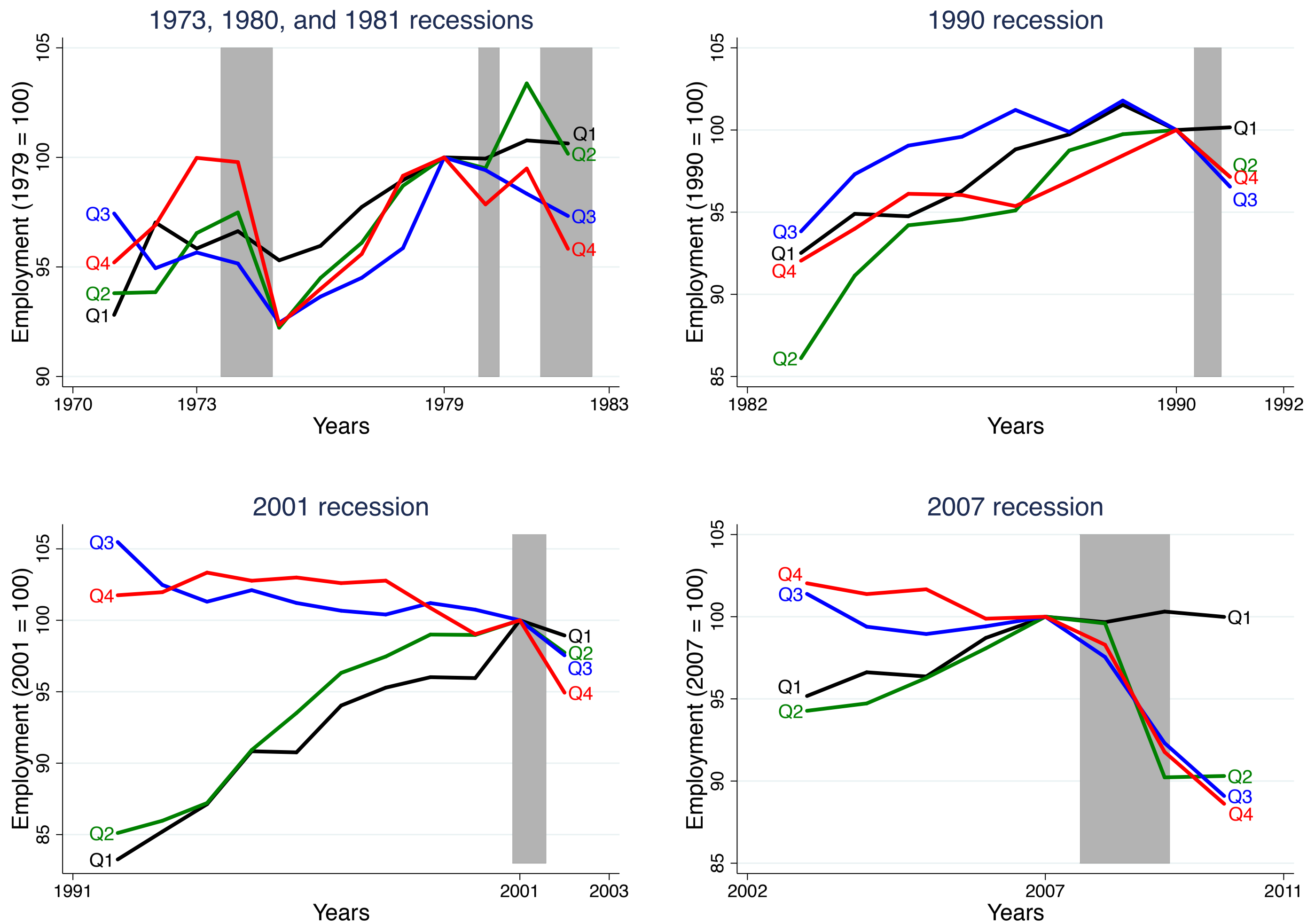


Figure 1.6: The Current Population Survey also displays an acceleration of the decline in routine occupations during recent recessions.

Details: "Q#" is quartile #, (see text for the definition of employment quartiles). Source: Current Population Survey and Occupational Information Network. Shaded areas are NBER recessions.

average of 0.71% for early recessions to an average of -0.04% for late recessions.

The model over-predicts the joblessness of the recovery after the 2007 recession compared to the data in Figure 1.1. One possible explanation is credit market disruptions caused firms to lay off more workers (Chodorow-Reich, 2014). With the end of the financial crisis, firms may have used their credit access to hire back laid off workers, a mechanism that is absent from the model. Another possible explanation is that the model pools together nonroutine jobs at the top and bottom of the skill distribution and both types of jobs are hoarded during the recession. In reality, nonroutine jobs at the bottom of the distribution may be fired during the recession and hired back in the recovery, causing the model to understate the recovery of employment.

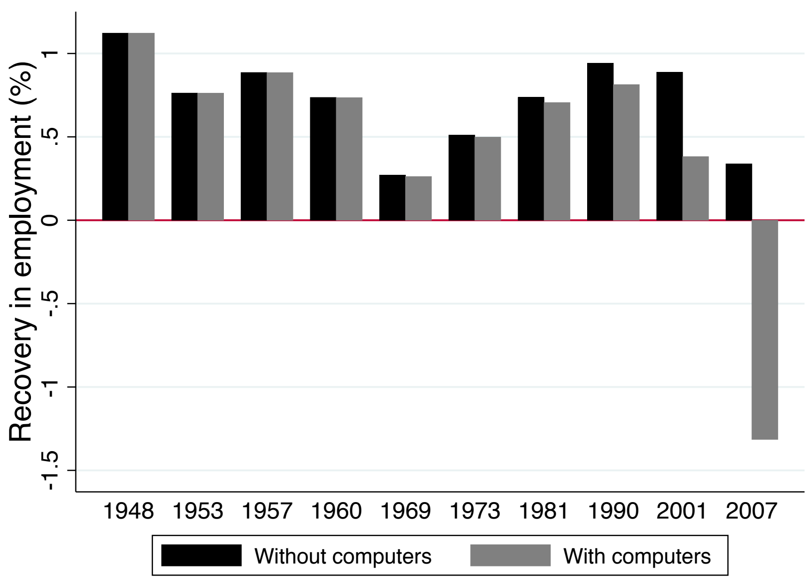


Figure 1.7: The model with computers predicts weaker recoveries of employment after recent recessions compared to the model without computers.
Details: recovery of employment for a given recovery of output of 5%, as in Figure 1.1.

1.5 Conclusion

This chapter studies the link between computers and the behavior of the labor market in the medium-term and the short-term. The model matches three structural changes in the labor market since the 1980s: a shift away from routine occupations, a productivity speed-up, and a decline in the labor share of income. The model also matches two cyclical changes: routine job losses concentrated in recessions and jobless recoveries.

The model predicts that these labor market changes should occur in all countries, since the decline in the price of computers was a global trend. Using industry-level data from the United States, Japan, and Europe, Michaels, Natraj and Reenen (2010) find that industries that invest more in computers also increase demand for nonroutine, highly-educated workers and decrease demand for routine, middle-educated workers. Furthermore, countries that invest more in computers, such as the United States, the United Kingdom, Sweden, and Japan, have also experienced jobless recoveries since the 1980s. Countries may invest differently in computers because, as Bloom, Sadun and Reenen (2007) suggested, computers complement the managerial practices in the United States but not in Europe. The model could capture these differences across countries i with a parameter λ_i in front of computer capital $K_{C,i,t}$. This parameter would affect the relative price of computers and could account for the distinct timing of computer adoption and labor market changes. Using the model to fit the cross-country evidence is left for future research.

Are jobless recoveries the new norm? Jaimovich and Siu (2012) think so,[23] but this chapter suggests a qualified conclusion: if the decrease in the price of computers slows down before the next recession, the following recovery may well be "jobful."

If the next recession occurs before this slowdown, the recovery may be jobless and this chapter suggests a new tradeoff for monetary authorities during jobless recoveries. In a

[23] "Jobless recoveries may be the new norm," from VoxEU article "Jobless recoveries and the disappearance of routine occupations" of 6 November 2012.

more general model with sticky prices, the interest rate is the cost of present consumption and also the cost of capital. If the monetary authority keeps interest rates low, it encourages firms to invest in computer capital instead of creating routine jobs; if it raises interest rates, there may be no recovery at all. An analysis of this tradeoff is left for future research.

Chapter 2

Electricity adoption and the Great Depression

2.1 Introduction

The first chapter of this dissertation focused on changes in the US labor market since the 1980s: structural changes such as a shift away from routine and automated occupations, a productivity speed-up, and a decline in the labor share of income; and cyclical changes such as routine job losses concentrated in recessions and jobless recoveries. The US labor market also experienced structural and cyclical changes in the 1920s and 1930s. States with higher rates of electricity adoption also decreased more the share of dexterity-intensive, repetitive occupations that follow explicit rules, such as laborers on the factory floor who could be replaced by the conveyor belt, compared to occupations with limited scope for replacement with electrical machinery, such as managers and clerks (Gray, 2013). Furthermore, the growth rate of labor productivity increased during the 1930s (Field, 2003). Finally, the US labor market also experienced jobless recoveries from recessions in the 1930s: the New York Times invented the expression in 1938 (see the literature review at the end of the introduction).

In contrast to the first chapter, which focused on theory and computers since the 1980s, this chapter focuses on identification and electricity in the 1930s. Testing the model in the context of electricity has several advantages compared to computers: electricity prices vary across regions depending on the source of power (hydroelectric or coal) but computers prices are the same everywhere; electricity is a homogenous good requiring no hedonic price adjustments; and electricity is measured with consumption instead of initial investment. This test also disentangles technology from competing explanations for labor market changes in the 1980s, such as offshoring (Elsby, Hobijn and Sahin, 2013) and unionization (Berger, 2012): in the 1930s, offshoring was infeasible and unionization rates were increasing (Farber and Western, 2000).

This chapter uses the same model as the first chapter, replacing computers with electricity, the 1980s with the 1930s, and the occupations that can be replaced by computers with those that can be replaced by electrical machinery. The literature on economic history of electrification supports the main assumptions of the model: a decrease in the price of electricity and substitutability between electrical machinery and some types of jobs. Gordon (1992, Table 1) estimates that the real price of electricity decreased at 7% per year between 1899 and 1948, while the Historical Statistics of the United States provide an estimate of 5.8% between 1902 and 1950 (see Appendix B.2.3). Goldin and Katz (2010, page 112) cite the example of laborers on the factory floor who were replaced by the conveyor belt, while Jerome (1934) documents the introduction of labor-saving machinery in many industries. To emphasize the parallels with the recent period, this chapter also labels these jobs as *routine*, even though the occupations may be different.

As an overview of the medium-term implications, the model matches the structural changes in the 1930s with these two assumptions. As electrical machinery becomes more competitive compared to workers, firms replace one with the other. The trend of automation causes employment to shift away from routine occupations, which substitute technology, and into nonroutine occupations, which complement technology. The same decrease in the price of electricity has a larger effect on the growth rate of labor productivity when electricity is cheap—because firms replace workers in routine occupations with electrical machinery—than when electricity is expensive—because firms forego investment in electrical machinery and hire workers in routine occupations instead. The price of electricity has a level effect: the same decrease in the price from a lower level causes a higher increase in the growth rate of labor productivity, which explains the productivity speedup of the 1920s and 1930s.

As an overview of the short-term implications, the model matches the cyclical changes with the additional assumption of labor market frictions. Firms know that they will have to hire more nonroutine jobs in the medium-term. If they destroy nonroutine jobs during the recession, they know that they will have to hire them back in the recovery and pay a hiring cost. To avoid the hiring costs, firms hoard nonroutine jobs during the recession and the burden of adjustment falls on routine jobs. Routine jobs do not entail this hiring cost in the recovery because of their declining trend. Firms did not lay off workers in nonroutine occupations during the recession, so they do not hire them back in the recovery. They may hire back workers in routine occupations but, since the medium-term trend of employment in routine occupations is decreasing, routine jobs do not recover back to peak. Total employment is constant, even as output recovers, which is the definition of a jobless recovery.

The crucial assumption underlying this behavior of the model is the substitutability between routine jobs and electrical machinery. If electrical machinery is equally substitutable to routine and nonroutine jobs, as with a Cobb-Douglas production function, then the model predicts a constant trend for the routine share of employment, the labor share of income, and productivity growth. When a business cycle shock vanishes, the economy returns to the constant trend, so recessions and recoveries have the same dynamics independently of the price of electricity.

This chapter uses the labor share of income to test this crucial assumption of substitutability between routine jobs and electrical machinery. If the elasticity of substitution between electrical machinery and routine jobs is greater than 1, the labor share of income should decrease as electricity becomes cheaper; if the elasticity of substitution between electrical machinery and all jobs equals 1—as in a Cobb-Douglas production function—the labor share of income should be unrelated to the price of electricity.

The ideal test of the model would be a random assignment of input prices across regions and a subsequent analysis of the labor market outcomes. Compared to this ideal test, the first part of the identification strategy uses geography as an instrument for the change in the price of electricity in the 1930s. Electricity at this time came either from hydroelectric power or coal power. Hydroelectric power had high efficiency in 1930, extracting 90% of the potential energy of falling water, and had few opportunities for cost savings. Coal power had low efficiency, extracting 25% of the thermal energy of coal, and had many opportunities for cost savings.[1] The price of electricity decreased in regions with coal power, such as New Jersey, but not in regions with hydroelectric power, such as California. A state's initial loading on coal power is an instrument for the supply-side change in the price of electricity.

The second part of the identification strategy consists of choosing the concrete industry, whose location decisions are orthogonal to the geography of electricity prices. Concrete plants produce a non-traded good and locate near their customers rather than near cheap electricity. The industry has high transport costs (ready-mix concrete, for example, has to be conveyed to the final location in a few hours) and is the third most non-traded industry

[1]National Electric Light Association (1931, page 43).

according to a Gini locational coefficient in 1935.[2] Concrete plants locate in New Jersey or California to be close to their customers, after which they react to the change in the price of electricity in each state. Measurements of labor market outcomes for the concrete industry provide a quasi-experiment to assess the causal effect of technical progress in electric utilities on downstream industries.

This chapter uses the universe of concrete plants from the Census of Manufactures, from 1929 to 1935, digitized for the first time for this project. It has information on employment, wage-bill, revenue, cost of electricity, consumption of electricity, and the number and horsepower of electric motors. Linking plants across years produces a panel of 742 continuing plants.

The instrumental variable regressions document that technical progress in the electric utility industry caused a decline in the labor share of income of the concrete industry and an increase in the use of electric motors, consistent with the mechanism of capital-labor substitution in the model. As a reminder, a Cobb-Douglas production function has constant factor shares: a decrease in the price of an input leaves the other input shares unaffected. The empirical result in this chapter is consistent only with a production function where the elasticity of substitution between electricity and labor is greater than 1. This substitutability is the crucial assumption of the theoretical model, which can in turn explain other features of the 1930s: the productivity speedup, structural changes in employment, and jobless recoveries. To buttress the technological explanation for labor

[2] The Gini locational coefficient (Holmes and Stevens, 2004, page 2810) measures the difference between the distribution of economic activity compared to population. Denote the number of states with N, the share of population in state k as pop_k, and the share of activity (number of plants or total employment) state k for industry i as act_{ki}. Define the location quotient LQ as the ratio of activity to population: $LQ_{ki} = act_{ki}/pop_k$. Order the share of activity by non-decreasing order of location quotients: $LQ_{1i} \leq LQ_{2i} \leq \cdots \leq LQ_{Ni}$. The Gini inequality coefficient for industry i is:

$$\text{Gini}_i = 1 - \sum_{k=1}^{N} pop_k \times \left(act_{ki} + 2 \sum_{l=k+1}^{N} act_{li} \right).$$

market changes, this chapter also estimates the effect on other variables. The instrumental variable and reduced-form regressions suggest that technical progress in the electric utility industry caused a decline in employment and in average wages of concrete plants.

Related literature. This chapter relates to several strands of the literature: electrification during the 1930s, the parallels between electricity and computers, and the jobless recovery from the Great Depression. On electrification in the 1930s, several studies have used aggregate-level data or Ordinary Least Squares to assess the effects of electrification on the labor market. Gray (2013) studied worker-level evidence from the first half of the 20th century and found that electrification was correlated with a shift away from occupations intensive in dexterity skills, similar to the findings of Autor, Levy and Murnane (2003) for computerization in the late 20th century. Field (2003) used aggregate-level growth accounting and argued that the 1930s had an unprecedented increase in TFP and were the "most technologically progressive decade of the century" because of electricity. Woolf (1984) used industry-level data from the Census of Manufactures between 1909 and 1929 and found that "firms sought labor-saving and capital-using techniques in response to cheaper energy ... [and reduced] labor's share of income." The evidence from previous studies is consistent with the thesis of this chapter, whose contribution is to use plant-level data and a new instrument for the adoption of electricity.

This chapter also relates to the literature on the parallels between electricity and computers. David (1990) argued that both electricity and computers generated productivity growth in the wider economy after a long lag, causing the productivity speedups of the 1920s and 1990s. Syverson (2013) found that the speedup in labor productivity of the 1990s was of a similar magnitude as that of the 1920s, documented by Kendrick (1961, page 71).[3]

[3]Field (2011, page 25) questioned the exact dating of the productivity speedup of Kendrick because of his choice of dates: "The problem is that Kendrick compared a fully employed economy in 1929 with a 1937 economy in which 14.3 percent of the labor force was still out of work ... If we seek a peacetime peak-

This chapter also relates to the literature on the jobless recovery and technological unemployment during the Great Depression. Irving Fisher in 1928 proposed technology as an explanation for the jobless recovery from the 1927 recession: "increased productivity per worker, aided by improved machinery and organization and more willing labor, is partly responsible for the anomaly of growing unemployment during an extended period of increased business activity" (quoted by Woirol, 1996, page 28). Keynes coined the term of "technological unemployment": "unemployment due to our discovery of means of economising the use of labour outrunning the pace at which we can find new uses for labour." Frances Perkins, secretary of the Department of Labor, stated in a Congressional testimony in 1935 that "you would be surprised at the number of labor-saving devices which have been introduced in industry in the last 2 or 3 years" (Committee on Finance, 1935, page 206). The New York Times invented the expression "jobless recovery" in the 1930s: "During November [of 1938, the Works Progress Administration] rolls showed some decline, but it was slight enough to make observers wonder whether the country were experiencing a 'jobless recovery."'[4] Relative to this literature, the contribution of this chapter is to suggest the decline in the price of electricity as the reason for technological unemployment.

2.2 Data and definitions

This chapter assesses the effect of technical progress in electric utilities on labor market variables. It uses two data sources at the state-level from publications by the Census Bureau and at the plant-level from micro-data at the National Archives. The Census Bureau published a state-level summary of the electric light and power industry in 1927

to-peak comparison, we are better served by choosing as an endpoint 1941, when unemployment, although still averaging 9.9 percent, was closer to what it was in 1929 but before war spending or production could seriously have influenced the economy."

[4]Article "Jobless recovery?" of 27 November 1938.

and 1937. It also published state-level information on other variables, such as the generation of electricity (hydroelectric or coal) in the Statistical Abstracts of the United States and wages in manufacturing in 1929 and 1935 in the state- and industry-level publications of the Census of Manufactures.

The plant-level dataset is from the Census of Manufactures in 1929 and 1935, which covers the universe of manufacturing plants with sales above five thousand dollars.[5] This dataset is at the National Archives and Records Administration in Washington D.C. Two barriers prevent the wider use of this dataset: the schedules are in paper or microfilm format and the National Archives protect them with in-house access only. This chapter focuses on the concrete industry, digitized for the first time for this project. I scanned all the microfilm schedules (around 2,500 for 1929 and 1,100 for 1935). The archivists marked as lost one microfilm roll with 300 plants in 1935 for states Alabama to Iowa but I was able to locate a backup copy in a different location. No schedules from the Census of Manufactures are missing from my sample. A professional data entry firm tabulated these schedules into electronic format. I verified the tabulations and corrected outliers, such as missing commas in the separation of cents and dollars. I also cleaned the names of states, counties and cities. The Census Bureau had no unique plant identifier and I matched the plants across years based on their name, location and ownership (see Appendix 2.2). From the 3,500 plants present in both 1929 and 1935, I obtained a panel of 742 continuing plants.

The concrete industry has three advantages for identification. First, it sells non-traded products (Syverson, 2004), which guarantees that concrete plants locate near their customers and their geographic distribution is exogenous to the regional variation in the price of electricity. Second, the concrete industry is intensive in electricity: continuing plants spent on average 1.3% of revenue in electricity in 1929. According to the electricity share

[5]This threshold in 1929 corresponds to around $66 thousand today and is high above the average sales for the concrete industry of $38 thousand in 1929 prices.

of value added at the industry level, concrete is in the upper third of manufacturing industries that use the most electricity. Third, concrete plants are small and bought all of their electricity from the grid: the Census Bureau asked about generation of electricity, which is zero for all firms in the balanced panel.

The Census asked about production by quantity and value, employment, wages, number of electric motors, horsepower of electric motors, kilowatt-hours purchased and their cost, and kilowatt-hours generated. The top panel of Table 3.2 shows summary statistics for continuing concrete plants. The concrete industry has many small plants, with an average of 13 employees. The bottom panel shows summary statistics for the change between 1929 and 1935. On average, concrete plants had a decrease in output, the labor share, employment, the price of electricity, and kilowatts-purchased. They also had an average increase in the number and horsepower of electric motors.

Concrete plants use labor-saving electrical machinery at several stages of production of concrete: machinery for crushing and grinding stones into a finer aggregate, machinery for pumping and unloading units to convey cement, electric power shovels and conveyor belts or elevators to move materials, mixing machines that produce a more homogenous product with less cement compared to manual mixing, and waste-heat boilers (Jerome, 1934, page 80; Orchard, 1962, page 404).

The concrete industry had a decline in the labor share of revenue of 14 percentage points, from 28.7% in 1909 to 14.4% in 1939, illustrated in Figure 2.1. Half of this decrease, or 7 percentage points, occurred during the Great Depression. The other half occurred during the other recessions of 1927 and 1937. The labor share of value added also decreased but its measure is less precise, as value added may include or omit spending in fuel and energy depending on the years.

Summary statistics for 1929

Number of plants	Employment of all plants	Average employment per plant	Electricity share of income	Electricity and fuel share of income	Kilowatt hours purchased
742	9,367	13	1.3%	2.4%	17,766

Summary statistics for the change between 1929 and 1935

Change from 1929 to 1935 (log-points)	Mean	S.d.
Output value	-0.56	0.87
Labor share	-0.11	0.56
Employment	-0.26	0.80
State-level cost of electricity	-0.23	0.06
Number of electric motors	0.14	0.61
Horsepower of electric motors	0.12	0.77

Table 2.1: Summary statistics for the concrete industry.

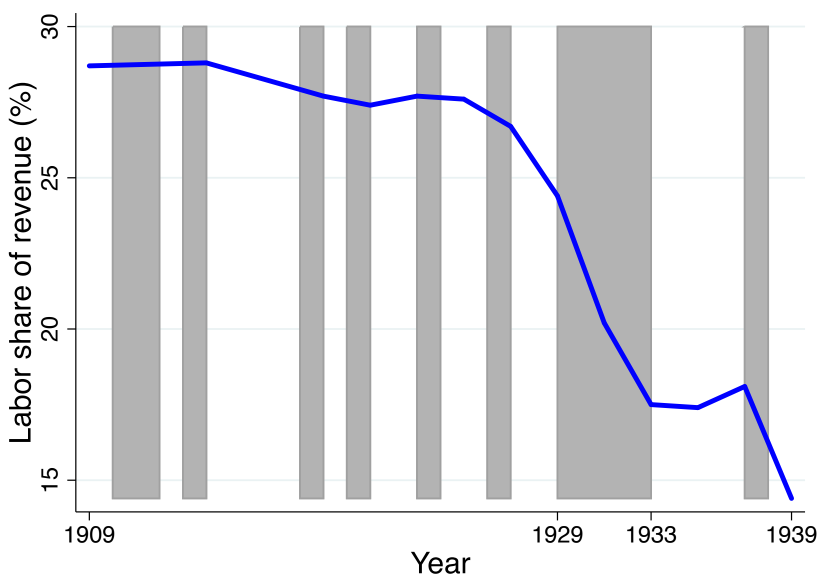


Figure 2.1: The decline in the labor share of revenue of the concrete industry accelerated during the Great Depression.

Details: wages divided by revenue every two years from 1909 to 1939, from the publication Census of Manufactures for the year 1939. Shaded areas are NBER recessions.

2.3 Methodology

2.3.1 Overview of the model

This subsection summarizes the production side of the theoretical model. The General Equilibrium properties of the model (household side and equilibrium of the labor, product, and capital markets) are omitted here and the interested reader is referred to the first chapter.

Plant i rents two types of capital, electric capital $K_{E,i,t}$ and non-electric capital $K_{NE,i,t}$. The first assumption is a long-term decrease in the rental rate of electric capital.

Assumption 12. *The rental rate $r_{E,i,t}$ of electric capital decreases exogenously with time:*

$$r_{E,i,t} \searrow \textit{ in } t.$$

Plant i hires workers in two types of occupations, routine occupations $L_{R,i,t}$ and non-routine occupations $L_{NR,i,t}$. The production function of plant i is:

$$\begin{aligned} Y_{i,t} &= A_{i,t}\ K^{\alpha}_{NE,i,t}\, L^{\beta}_{NR,i,t}\, M^{\gamma}_{i,t}, \\ M_t &= \left(K^{\frac{\sigma-1}{\sigma}}_{E,i,t} + L^{\frac{\sigma-1}{\sigma}}_{R,i,t}\right)^{\frac{\sigma}{\sigma-1}}, \end{aligned} \tag{2.3.1}$$

where $A_{i,t}$ is Total Factor productivity. The production function has constant returns to scale, with $\alpha + \beta + \gamma = 1$. This production function has Cobb-Douglas aggregation of three factors: non-electric capital $K_{NE,i,t}$, employment in nonroutine occupations $L_{NR,i,t}$, and a third factor, which is a Constant-Elasticity-of-Substitution aggregate between electric capital $K_{E,i,t}$ and employment in routine occupations $L_{R,i,t}$. The second crucial assumption is gross substitutability of electric capital and employment in routine occupations tasks in the production function:

Assumption 13. *The elasticity of substitution between electric capital and employment in routine occupations is greater or equal to 1:*

$$\sigma \geq 1.$$

Plant i operates under perfect competition and has profits

$$\text{profits}_{i,t} = p_{i,t}Y_{i,t} - w_{i,t}\left(L_{NR,i,t} + L_{R,i,t}\right) - r_{NE,i,t}K_{NE,i,t} - r_{E,i,t}K_{E,i,t},$$

where $w_{i,t}$ is the wage, $p_{i,t}$ is the price of output. The firm maximizes the present value of profits, discounted with the market interest rate r_t.

Like the first chapter, the wage $w_{i,t}$ is the same for routine and nonroutine occupations because the household is perfectly indifferent between the two tasks. Unlike the first chapter, hiring costs are zero in this setting, which guarantees a closed-form solution. The interested reader is referred to the first chapter for more details on the supply side of the labor market and the more general version of the model with adjustment costs.

2.3.2 Testable predictions

The first chapter shows that the General Equilibrium model with hiring costs has five predictions for the labor market: (1) the labor productivity speeds up, (2) employment shifts away from routine occupations and into nonroutine occupations, (3) the labor share of income declines, (4) recessions accelerate the structural decline in routine occupations, (5) recoveries from recessions are jobless, i.e. employment recovers slower than output.

Testing the theory requires choosing the predictions to test with the available data. One prediction of the model—routinization of production—is the subject of Gray (2013).

She merged the worker-level Census of Population from 1900 to 1950 to the Dictionary of Occupational Titles. She defined an occupation as routine if it required high dexterity and low manual or clerical skills. She found that states with faster electrification also shifted away from these routine occupations, similar to the findings of Autor, Levy and Murnane (2003) for computerization in the late 20th century and consistent with the thesis in this chapter.

The prediction of acceleration of routinization cannot be tested with this dataset. This prediction requires high-frequency information on employment by detailed occupations, which is unavailable in the Census of Manufactures (see Appendix B.1.3). If electricity complements nonroutine occupations, the positive impact on nonroutine jobs could offset the negative impact on routine jobs, which biases against finding a positive net effect.

Two other predictions—labor productivity speedup and jobless recoveries—find some support in the data but have measurement problems. Measures of quantity productivity among concrete plants have poor quality: the Census Bureau asked plants to report the tons of concrete but plants often reported other units. Table B.2 in the Appendix suggests that the decrease in the price of electricity caused an increase in labor productivity, with a coefficient that is statistically significant at the 10% level. On jobless recoveries, an unreported regression of employment between 1933 and 1935 suggests that regions with cheaper electricity also had a slower recovery in employment, but the coefficients are statistically insignificant because output is the major determinant of employment and omitting it increases the variance of the regression.

The last prediction bears on the labor share of income. This variable has accurate measures in the Census of Manufactures: the Census Bureau verified the schedules, asked plants reporting high or low wages to confirm the values and remove typographical errors. Testing this prediction on the labor share of income is the focus of the rest of this chapter.

The period covered is 1929 and 1935 for three reasons. First, the plant schedules of the Census of Manufactures survived only for this period and the remaining years were destroyed. Access to plant-level data is important in order to link plants across years and avoid compositional bias due to the turnover of plants. Second, the model predicts that recessions accelerate the medium-term decline in routine jobs. Deep recessions should render this pattern of capital-labor substitution clearer than mild recessions. Third, the major turmoil in labor markets during the Great Depression provides variation in the dependent variables and allows a more precise estimation of the regression coefficients.

2.3.3 Linear regressions

The model implies the following non-linear equations for the labor share of income and the electric capital-labor ratio (see Appendix B.3):

$$\frac{w_{j,t}L_{j,t}}{p_{j,t}Y_{j,t}} = \beta + \gamma \left(1 + \left(\frac{r_{E,j,t}}{w_{j,t}}\right)^{1-\sigma}\right)^{-1}, \tag{2.3.2}$$

$$\frac{K_{E,j,t}}{L_{j,t}} = \left(\frac{r_{E,j,t}}{w_{j,t}}\right)^{-1} \left(\frac{\beta}{\gamma} + \left(1 + \frac{\beta}{\gamma}\right)\left(\frac{r_{E,j,t}}{w_{j,t}}\right)^{\sigma-1}\right)^{-1}, \tag{2.3.3}$$

where j indexes a unit of observation such as firms i or regions k (see Appendix B.3 for proofs).

These equations include a "level effect:" when electrical machinery is too expensive and $\sigma > 1$, the non-linear term vanishes from the equation and the labor share of income is constant. When technology is too expensive, a decrease in the price of electricity has little impact on the economy, as firms prefer to hire workers instead. The "level effect" was discussed in the first chapter.

To translate these predictions into regression equations, I consider the log-linear version of the equations. The problems in using a log-linear version of non-linear equations with a level effect are minimal because the level effect is more important over decades of decrease in the price of the technology, rather than the six years between 1929 and 1935. The next simulations illustrate that the log-linear regressions are an accurate approximation to the non-linear relationships, I use the General Equilibrium model from the first chapter to simulate 300 artificial economies. All simulations use the same parameters, equal to those from the calibration in the first chapter, except for the rate of decrease ϕ in the price of electricity, which follows a uniform distribution between 1% and 18%. I solve the model for each artificial economy j and estimate the following log-linear equations:

$$\Delta \log \frac{w_{j,t} L_{j,t}}{p_{j,t} Y_{j,t}} = 0.0011 + 0.047 \, \Delta \log \left(\frac{r_{E,j,t}}{w_{j,t}} \right) + error \tag{2.3.4}$$

$$\Delta \log \frac{K_{E,j,t}}{L_{j,t}} = -0.0023 - 1.556 \, \Delta \log \left(\frac{r_{E,j,t}}{w_{j,t}} \right) + error \tag{2.3.5}$$

Under the assumption $\sigma > 1$, the slope coefficient should be positive for the labor share of income and smaller than -1 for the computer capital-labor ratio. The scatter plot in Figure 2.2 shows that the log-linear regression from the model is an accurate approximation to the non-linear expression.

Two further difficulties arise in the context of electricity. First, the rental rate $r_{E,j,t}$ of electrical machinery is unobserved and I use the price of electricity in cents per kilowatt-hour as a proxy, which implies measurement error and an attenuation bias toward zero.[6] Second, the average price of electricity at the plant-level is far from the marginal price: several forms of fixed costs (see Appendix B.2) introduce measurement error in the price of electricity paid by concrete plants, which are small with an average of 12 employees. Fixed costs should lose importance when considering a larger entity such as the state, whose

[6]The usage cost of electricity has two components: the price of electricity in kilowatt-hours and the rental rate of an electric motor. Regional variation in the usage costs stems mostly from the price of electricity because the rental rate of electric motors is likely to be the same for all regions. The rental rate of an electric motor has three components: the interest rate, the price of investment, and the depreciation rate. Each of these components should have similar values across regions: the interest rate was set by the Federal Reserve for all regions and the electrical machinery industry was concentrated in five states which served a national market with similar investment prices and depreciation rates.

average price of electricity should be closer to the marginal price. The preferred measure of the price of electricity is the state-level average price from the Census of Electric Light and Power Stations for 1927 and 1937.[7] This measure minimizes the importance of fixed costs, making the average price closer to marginal price, and is close to the price of electricity paid by industrial users, since power stations sold on average 69% of their current to industrial consumers.[8]

The regression equations for electricity are:

$$\Delta \log \frac{w_{i,t} L_{i,t}}{p_{i,t} Y_{i,t}} = constant + a\,\Delta \log \left(\frac{p_{E,k,t}}{w_{k,t}}\right) + error. \tag{2.3.6}$$

$$\Delta \log \frac{K_{E,i,t}}{L_{i,t}} = constant + a' \Delta \log \left(\frac{p_{E,k,t}}{w_{k,t}}\right) + error \tag{2.3.7}$$

where i indexes plants, k indexes states, $w_{i,t}L_{i,t}$ is the aggregate wage-bill at the plant-level, $p_{i,t}Y_{i,t}$ is the total value of output at the plant-level, $p_{E,k,t}/w_{k,t}$ is the change in the price of electricity relative to the wage at the state-level, and $K_{E,i,t}/L_{i,t}$ is a measure of the electric capital-labor ratio at the plant-level. Note that the left-hand side of (2.3.6) uses the wage at the plant-level for the concrete industry and the right-hand side uses the wage at the state-level for all manufacturing industries. The theory predicts $a > 0$ and $a' < -1$: a decrease in the price of electricity or an increase in the wage cause a substitution into electricity and a decrease in the labor share of income. The model normalizes the price of output $p_{i,t}$ to 1, so other prices are in real terms. The regressions use a nominal price with no deflator—deflating prices by a nation-wide price or wage index would affect the intercept of the regression and not the slope.

[7] Stigler and Friedland (1962) used this measure to assess the effect of regulation on electricity prices. To the best of my knowledge, the Census of Electric Light and Power Stations is the only source of data for the price of electricity at the state-level during this period.

[8] Census of Electric Light and Power Stations, 1927, page 51.

2.3.4 Endogeneity and an instrument

The identifying assumptions for regression equations (2.3.6) and (2.3.7) are that the average price of electricity, of labor, and of output are close to the marginal prices and that the error term is uncorrelated with the regressors. Then a and a' are consistent and unbiased estimators.

Estimating a regression of quantities on prices raises concerns about endogeneity and is a challenge to identification: it is unclear whether the regression estimates the demand or supply equation. This chapter is interested in the demand for electricity and requires an instrument that shifts the electricity supply curve and not the demand curve. This endogeneity should bias the estimation of the downward-sloping electricity demand curve toward the upward-sloping electricity supply curve. The coefficients should be further away from zero in Instrumental Variables (IV) compared to Ordinary Least Squares (OLS). A similar argument suggests that endogeneity also biases the coefficient on the labor share of income toward zero because the labor share of income is decreasing in the electric capital-labor ratio in the model.

The identification strategy to deal with the endogeneity bias consists of two parts: using geography as an instrument for the change in the price of electricity and choosing the non-traded industry of concrete. As an instrument for the supply-side change in the price of electricity, this chapter uses the share of coal in the generation of electricity in 1927. In 1930, power plants extracted 90% of the potential energy of falling water and had few opportunities for cost-saving innovations. Power plants extracted 25% of the potential energy of burning coal to power steam turbines, had many opportunities for cost-saving innovations.[9] The generation of electricity from coal improved thanks to a "rise in steam pressures and steam temperatures used, and ... the experimental introduction of a

[9]National Electric Light Association (1931, page 43).

second working fluid in an independent cycle supplementing that of the steam."[10] These innovations increased the thermal efficiency of fuel: "In 1928, the same amount of energy was produced with 71 per cent less fuel than would have been required in 1904."[11]

Technical progress in the generation of electricity from coal impacted regions differently depending on their initial dependence on this technology. Regions with access to hydroelectric power, such as Minnesota or California, have cheap electricity but the price of electricity is roughly constant. Regions without hydroelectric power, such as North Dakota or New Jersey, have initially more expensive electricity but the price of electricity decreases. Figure 2.3 illustrates the pattern of convergence across states. Figure 2.4 shows the first-stage of the instrument at the state-level: states with initially larger dependence on coal power also had a decrease in the relative price of electricity. The relative price of electricity in this chapter is

$$\Delta \log\left(\frac{p_{E,k,t}}{w_{k,t}}\right) = \frac{6}{10}\log\left(\frac{p_{E,k,1937}}{p_{E,k,1927}}\right) - \log\left(\frac{w_{k,1935}}{w_{k,1929}}\right),$$

where the price of electricity is the average price of electricity for all consumers from the Census of Electric Light and Power Stations in 1927 and 1937 and the wage is the industry-wide average wage for wage-earners and salaried workers for all manufacturing firms in 1929 and 1935.

Four arguments support the validity of this instrument. First, concrete plants do not sort geographically depending on the price of electricity: the concrete industry sells a non-traded product and locates near its customers. Second, the instrument should affect electric utilities on the supply side of the electricity market but not concrete plants on the demand side of the market. Third, the instrument is an initial level and the outcome variables are

[10] Census of Electric Light and Power Stations (1927, page 82)

[11] Electrical Research Statistics (1929). See also Sleight (1930, page 57) for a similar finding.

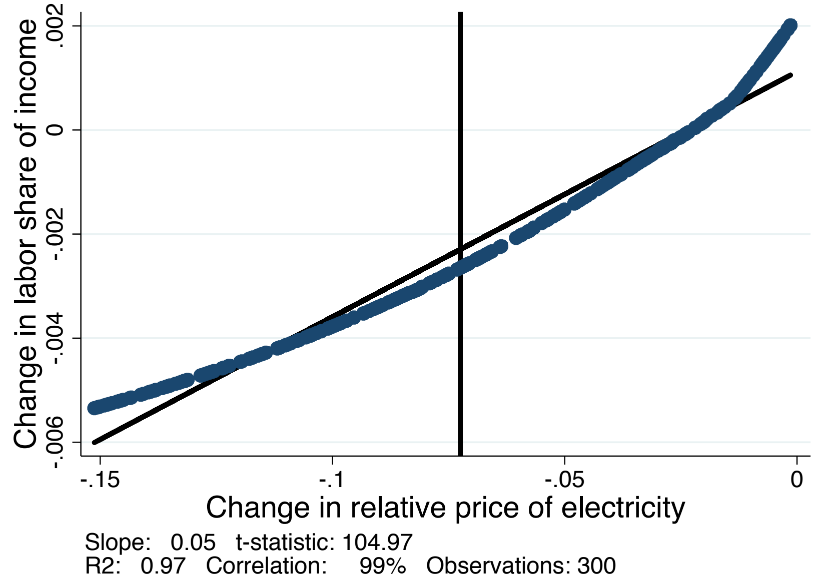


Figure 2.2: The non-linear relationship in the model is close to a linear one for short periods of time.

The vertical line corresponds to a decrease in the price of electricity of $\phi = 7\%$.

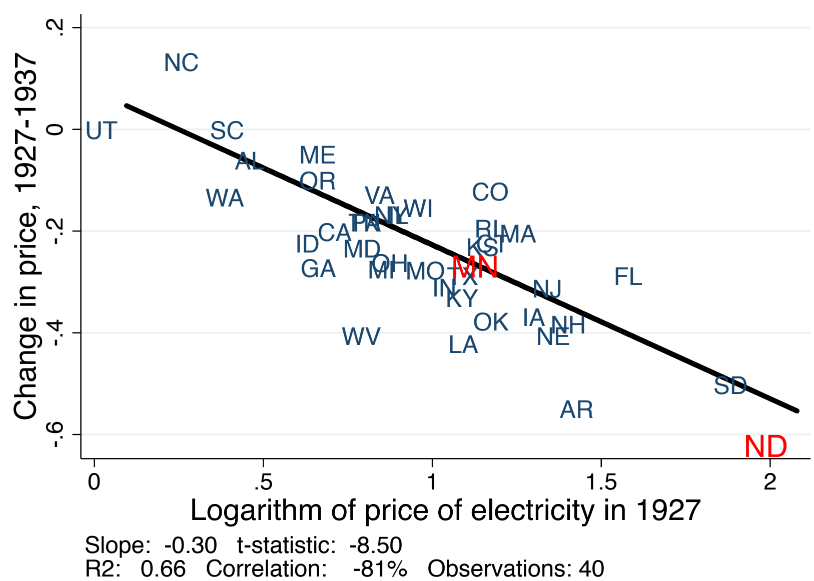


Figure 2.3: The price of electricity converged across states between 1927 and 1937.

The two neighboring states of Minnesota and North Dakota have a different color and a larger font. The outlier states of Mississippi and Arizona are omitted.

changes. Omitted variables in levels, such as the skill composition of the workforce or the density of the road network, are differenced out in the regressions. Fourth, using ratios at the plant-level, such as labor productivity or the labor share of income, implies the absence of that plant-level shocks that affect the numerator and denominator similarly, such as TFP shocks.

A possible violation of the exclusion restriction concerns omitted variables that change through time. For example, cities high in hydroelectric power may attract more government programs for dam construction, which would increase demand for concrete in regions with hydroelectric power compared to regions with coal power. This increase in demand may be met with the more adjustable factors, such as labor or materials. To address this concern, I run a falsification test with the materials share of income and also run a robustness test by dropping states with dam construction from the sample.

2.4 Results

This section presents the evidence for $\sigma > 1$ and for the causal link between electricity and the labor share of income. Concrete plants with access to cheaper electricity also reduce their labor share of income and invest more in electricity. The results are robust to including controls such as state-level initial GDP or the state-level share of agriculture.

2.4.1 Baseline results

Table 2.2 shows the results of the regressions using the change in the price of electricity relative to wages, in OLS, IV, and reduced-form. The coefficient on the price of electricity is between 0.6 and 0.9 and is statistically and economically significant. It should be positive under the assumption $\sigma > 1$ and zero under $\sigma = 1$. This regression supports the crucial assumption in the model. The F-statistic for the first-stage is in the confidence region above

10. Electricity has an IV coefficient with a higher magnitude than the OLS coefficient. This difference is consistent with the importance of demand shocks in the market for electricity during the Depression. The reduced-form regressions show an effect of initial dependence on coal power on the labor share of income: initially higher dependence on coal, which causes a decrease in the price of electricity, also causes a decrease in the labor share of income. The reduced-form coefficient on coal power is economically and statistically significant. The standard errors in all tables are clustered at the state-level.

With the elasticity of the labor share with respect to the price of electricity of 2 from the IV regressions, the predicted change in the labor share of revenue is $\Delta \log(wL/pY) = -0.23 \times 2 = -0.46$. The labor share of revenue for the aggregate-level concrete industry declined from 24.4% in 1929 to 17.4% in 1935. The IV estimates predict that the labor share of revenue should decrease to $24.4\% \times \exp(-0.46) = 15.4\%$, a magnitude similar to the data for the aggregate-level concrete industry. The predicted change of -0.46 is larger than the change in the labor share of revenue of continuing plants, at -0.11 from the summary statistics. This thought experiment assesses the net contribution of electricity and holds constant other factors, such as wages that may have national-level shifters such as the National Recovery Act of 1933.

2.4.2 Robustness

This section extends the baseline regressions above and shows robustness checks that support the technological explanation. To ensure that the variation in the relative price of electricity stems from the absolute price of electricity rather than the wage, Table 2.3 shows the regressions of the labor share with the absolute price of electricity. The electricity coefficient is similar and the F-statistic for the first-stage is still above 10.

Table 2.4 shows the effect of cheaper electricity on employment. Cheaper electricity also caused a reduction in employment of concrete plants, in Instrumental Variables and

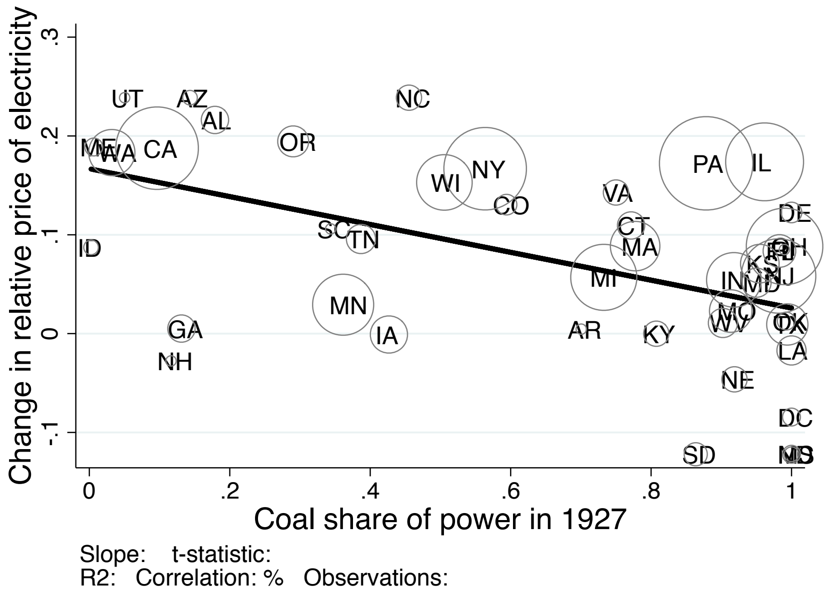


Figure 2.4: First-stage regression: an initially higher share of coal in power generation in 1927 causes a subsequent decrease in the relative price of electricity.

Larger circles represent states with more plants but the regression line has the same weight for all states.

Dependent variable: $\Delta \log (w_{i,t}L_{i,t}/p_{i,t}Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log (p_{E,k,t}/w_{k,t})$	0.695**	2.094**	
(state-level)	(0.277)	(0.843)	
$coal_{k,1927}$			-0.181***
(state-level)			(0.0598)
Constant	-0.184***	-0.335***	0.0167
	(0.0326)	(0.0923)	(0.0445)
Observations	733	733	733
R-squared	0.008		0.011
First-stage F-statistic		14.89	

Robust standard errors in parentheses (state-level clustering, 44 clusters)
*** p<0.01, ** p<0.05, * p<0.1

Table 2.2: Baseline regression: the decrease in the price of electricity caused a decrease in the labor share of income.

Details: a regression of the relative price of electricity on the instrument, at the state-level without clustering, provides the first-stage F-statistic for the IV regression.

in reduced-form, suggesting that technology may help accounting for reduced job creation and high unemployment during the Great Depression. Table 2.5 presents the results for the average wage. The decrease in the price of electricity put downward pressure on wages. The decrease in wages may be an additional channel for the adoption of technology to affect the macroeconomy.

Tables 2.6 shows a falsification test with the materials share of revenue. One might be concerned that, since revenue shares sum to one, the effect of electricity on the labor share may be a arithmetic consequence of the increase in the share of materials or fuel. These concerns are mitigated by a statistically significant effect of electricity on the labor share of revenue and a statistically insignificant on the shares for materials. Table B.3 in the Appendix shows similar results for the fuel share of revenue.

To ensure that the initial level of coal dependence is not capturing an alternative channel such as a demand shock, Figure 2.5 plots the change in building permits at the state-level between 1929 and 1935[12] against the initial coal dependence. The coal share of power is uncorrelated with this measure of a demand shock.

The baseline results are also robust to other specifications: using the fixed characteristic of hydropower potential as an instrument instead of the coal share of power in 1927, controlling for the price of inputs, using the labor share of value added instead of income, controlling for a county-level measure of the business cycle, for state-level GDP in 1929, and for the state-level share of population working in agriculture in 1920. These regressions are in Appendix B.4, which also estimates a positive effect of cheaper electricity on quantity labor productivity.

[12] The Bureau of Labor Statistics compiled building permits by year from 1921 to 1940 for 262 large cities in the United States. This dataset was digitized by Kimbrough and Snowden (2007).

Dependent variable: $\Delta \log (w_{i,t} L_{i,t} / p_{i,t} Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log p_{E,k,t}$	1.212***	2.958**	
(state-level)	(0.409)	(1.243)	
$coal_{k,1927}$			-0.181***
(state-level)			(0.0598)
Constant	0.058	0.298*	0.0167
	(0.0667)	(0.181)	(0.0445)
Observations	733	733	733
R-squared	0.012		0.011
First-stage F-statistic		16.72	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.3: The baseline results are robust to using the absolute price of electricity instead of the relative price.

Dependent variable: $\Delta \log (L_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log (p_{E,k,t} / w_{k,t})$	-0.0882	2.134*	
(state-level)	(0.418)	(1.123)	
$coal_{k,1927}$			-0.184***
(state-level)			(0.0595)
Constant	-0.248***	-0.488***	-0.130***
	(0.0571)	(0.136)	(0.0386)
Observations	733	733	733
R-squared	0		0.005
First-stage F-statistic		14.89	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.4: The decrease in the price of electricity may have caused a decrease in employment.

Dependent variable: $\Delta \log (w_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log (p_{E,k,t})$	0.638*	1.873**	
(state-level)	(0.318)	(0.868)	
$coal_{k,1927}$			-0.114**
(state-level)			(0.0485)
Constant	-0.326***	-0.157	-0.335***
	(0.0408)	(0.121)	(0.0296)
Observations	733	733	733
R-squared	0.005		0.007
First-stage F-statistic		16.72	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.5: The decrease in the price of electricity caused a decrease in wages.

Dependent variable: $\Delta \log (Materials_{i,t}/p_{i,t}Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log (p_{E,k,t}/w_{k,t})$	0.0407	0.807	
(state-level)	(0.215)	(0.742)	
$coal_{k,1927}$			-0.0691
(state-level)			(0.0529)
Constant	0.00994	-0.0735	0.0621
	(0.0308)	(0.0886)	(0.0387)
Observations	704	704	704
R-squared	0		0.002
First-stage F-statistic		14.89	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.6: Falsification test: the decrease in the price of electricity has no effect on the materials share of revenue.

2.4.3 Geography of the coal share of power

Using state-level geography as an instrument has the drawback that the instrument corresponds to inland regions as opposed to the coasts. Figure 2.6 shows that the mountains in the West and East Coast provide the altitude differentials necessary for hydroelectric power while the Great Plains need to use steam power.

Some variation persists within region, such as the neighboring states of North Dakota with 100% coal power versus Minnesota with 36% coal power, or the neighboring states of Florida with 98% coal power versus Georgia with 13% coal power. Nevertheless, the within-region variation is not sufficient to confirm the results of the labor share regressions: Table 2.7 shows that the baseline results do not hold when including fixed effects for the nine US Census divisions.[13]

Hydroelectric power requires falling water and is close to the map of mountains in the United States, a consequence of using geography as an instrument for the change in the price of electricity depending on the source of power. If plants in the mountain regions are affected differently during the Depression, it may invalidate the exclusion restriction of the Instrumental Variable approach. One possibility is that mountain regions have government programs for building dams.

Table 2.8 shows that the baseline results are robust to dropping counties within 50 miles of dams under construction, giving confidence that the instrument is valid and the results are not due to government demand for concrete products. The point estimates are similar when dropping counties within 100 miles of dams under construction but the sample size decreases to 439, which affects the statistical significance of the estimates.

Appendix B.4 also shows that the change in the plant-level price of electricity is positively correlated with the change in the plant-level labor share of income, even including

[13]The nine Census divisions in the United States are New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, and Pacific.

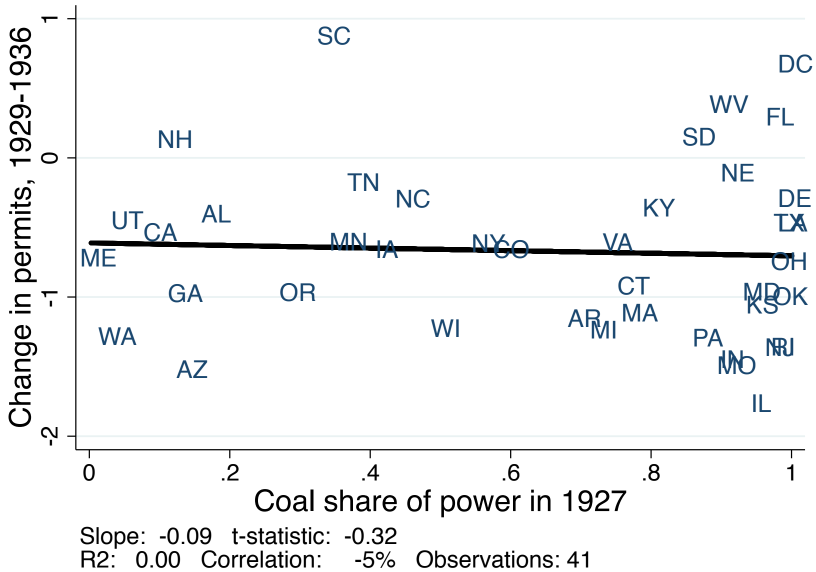


Figure 2.5: The coal share of power in 1927 is uncorrelated with the change in building permits from 1929 to 1936.

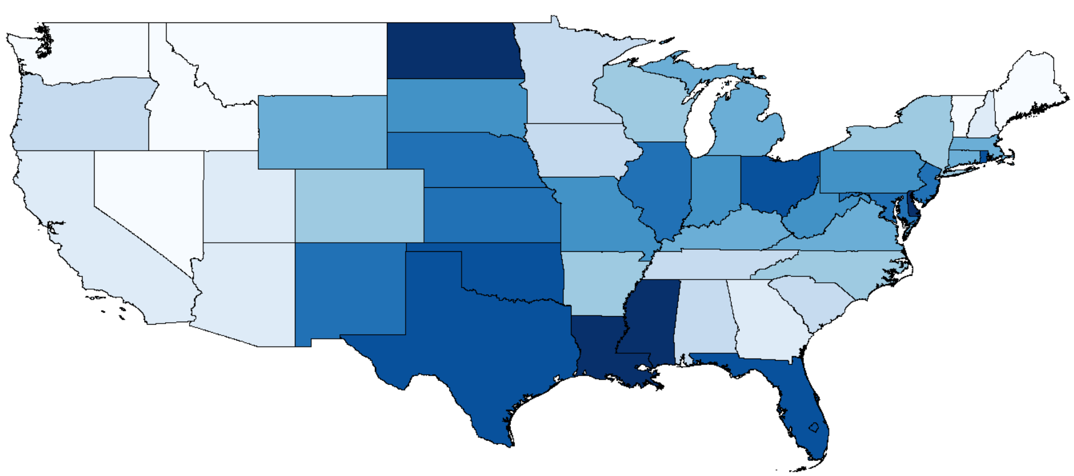


Figure 2.6: Map of the share of coal power in 1927.
Note: a darker blue implies a higher coal share.

Dependent variable: $\Delta \log (w_{i,t} L_{i,t} / p_{i,t} Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log (p_{E,k,t} / w_{k,t})$	0.745**	1.279	
(state-level)	(0.327)	(1.280)	
$coal_{k,1927}$			-0.0992
(state-level)			(0.103)
Constant	-0.283*	-0.335	-0.14
	(0.157)	(0.206)	(0.166)
Division dummies	Yes	Yes	Yes
Observations	733	733	733
R-squared	0.024	0.022	0.021
First-stage F-statistic		4.08	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.7: The effect of electricity on the labor share of income is sensitive to including dummies for the 5 divisions in the US.

Dependent variable: $\Delta \log \left(w_{i,t} L_{i,t} / p_{i,t} Y_{i,t} \right)$

Method:	OLS	IV	reduced-form
$\Delta \log \left(p_{E,k,t} / w_{k,t} \right)$	0.651**	2.314**	
(state-level)	(0.263)	(1.157)	
$coal_{k,1927}$			-0.177***
(state-level)			(0.0635)
Constant	-0.178***	-0.349***	0.0189
	(0.0324)	(0.122)	(0.0486)
Observations	623	623	623
R-squared	0.007		0.009
First-stage F-statistic		17.52	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.8: The baseline results are robust to dropping counties within 50 miles of dams under construction.

Details: The latitude and longitude by city is from Gaslamp Media (2014), which "compiled from a city/county/state database and geocoded with Google Maps." The list of counties with dam construction is from Hay (1991) for dams completed between 1930 and 1940. The latitude and longitude of a county with dam construction is the average of all cities in that county. The closest distance from county X to a dam under construction is the minimum Haversine distance from all cities in county X to all counties with dam construction.

state fixed-effects. These regressions are not identified but provide a within-state source of variation that confirms the baseline results.

Another threat to identification occurs if the share of coal in electric power generation reacts to changes in electricity demand and in aggregate demand. Appendix B.4 mitigates these concerns and shows that the results are robust to using hydroelectric potential by state as an instrument. Hydroelectric potential depends only on geography and does not react to changes in electricity demand.

2.4.4 Electricity usage

This subsection shows the effect of the change in the price of electricity on two measures of electricity consumption: the number of electric motors per worker and the horsepower of electric motors per worker. The IV regressions in Tables 2.9 and 2.10 trace the demand curve and find a negative coefficient: cheaper electricity induces a higher number of electric motors and with more horsepower. The theory predicts that the coefficients on electric capital-labor ratios should be smaller than -1 and the regressions confirm that prediction. The coefficients lack statistical significance possibly because of a smaller sample size: electricity variables are more rare than employment variables and even the labor share regressions lose some statistical significance when considering the sample of plants that report electricity variables in both years. For example, the effect of the instrument is statistically significant at the 1% level with all plants and statistically significant at the 10% level with the sample of plants reporting electricity variables.

The effect on kilowatts per worker is imprecisely estimated and is omitted. This measure may be problematic as it is absent for half the sample in 1935, was imputed with a linear regression from the number and horsepower of electric motors, and has reduced variation.

Dependent variable: $\Delta \log \left(motors_{i,t}/L_{i,t} \right)$

Method:	OLS	IV	reduced-form
$\Delta \log \left(p_{E,k,t}/w_{k,t} \right)$	0.452	-2.833	
(state-level)	(0.513)	(2.447)	
$coal_{k,1927}$			0.247*
(state-level)			(0.144)
Constant	0.408***	0.769***	0.290**
	(0.0787)	(0.260)	(0.118)
Observations	555	555	555
R-squared	0.002		0.009
First-stage F-statistic		15.07	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.9: The effect of the price of electricity on the number of electric motors per worker conforms to the theoretical prediction.

Dependent variable: $\Delta \log \left(horsepower_{i,t}/L_{i,t} \right)$

Method:	OLS	IV	reduced-form
$\Delta \log \left(p_{E,k,t}/w_{k,t} \right)$	0.23	-5.640*	
(state-level)	(0.669)	(3.313)	
$coal_{k,1927}$			0.494***
(state-level)			(0.142)
Constant	0.414***	1.056***	0.103
	(0.107)	(0.364)	(0.111)
Observations	552	552	552
R-squared	0		0.027
First-stage F-statistic		15.07	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.10: The effect of the price of electricity on the horsepower of electric motors per worker conforms to the theoretical prediction.

2.5 Conclusion

This chapter tests the model of labor market changes based on capital-labor substitution in the context of electricity and provides two contributions. First, it uses a plant-level dataset from the concrete industry during the 1930s, digitized for the first time for this project. Second, the identification strategy instruments shifts in the electricity supply curve with a state's initial loading on the coal technology. Consistent with the predictions of the model, a decrease in the price of electricity caused a decrease in the labor share of income. This result implies that the elasticity of substitution between electricity and labor is greater than 1. Some occupations may be more replaced by electrical machinery than others, such as the routine, dexterity-intensive occupations described by Gray (2013). With this assumption of substitutability between routine jobs and electricity, the model can also account for other changes of the US labor market during the Great Depression: structural changes in employment, a productivity speedup, job losses concentrated in recessions, and jobless recoveries.

This chapter relates to the literature on waves of technology throughout history: "whole eras of technical progress and growth appear to be driven by a few 'General Purpose Technologies,' such as the steam engine, the electric motor, and semiconductors." (Bresnahan and Trajtenberg, 1995). A recent debate has focused on the importance of recent General Purpose Technologies compared to previous ones. Jovanovic and Rousseau (2005) think that "electricity and information technology [are] probably are the two most important General Purpose Technologies so far." Gordon (1999) disagrees and suggests that we may face decreasing returns in the invention of new technologies: "electricity . . . was a much more profound creator of productivity growth than anything that has happened recently . . . this was a unique event that will not be replicated in the lifetimes of our generation or that which follows us." It is an open question whether the next General Purpose Technology will be as important as previous ones and whether the historical patterns of the output and labor markets will repeat themselves.

Chapter 3

Routinization and slow recoveries in consumption

3.1 Introduction

Recent recoveries in the United States have not only been jobless—they have also been slow. After the recessions of 1990, 2001, and 2007, the recovery of output from the NBER trough to two years after is low by historical standards, at 9% after the 1980s as opposed to 15% before. The slow recovery of output has been a puzzle for policymakers.[1] Figure 3.1 displays this pattern of slow recoveries in output and real consumption expenditures for nine postwar recessions.[2] Consumption also has a slower recovery after the last three recessions compared to previous ones. The dashed horizontal lines are 95% confidence intervals: the average recovery of consumption and output is significantly different between

[1]See the speech of 20 November 2012 by Federal Reserve Chairman Ben Bernanke, who mentions the "disappointingly slow pace of economic recovery in the United States."

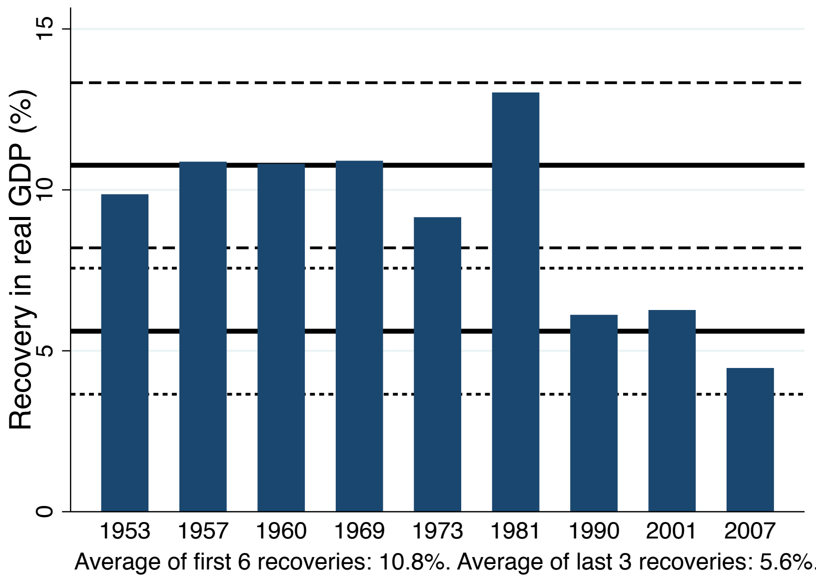
[2]I omitted the recoveries from the 1948 recession, from 1949 to 1951, which covered the beginning of the Korean War and had an output increase of 18% due to government expenditures, and the recovery from the 1980 recession, which was cut short by the 1981 recession.

early and late recessions.

A simple counterfactual exercise illustrates the importance of consumption in explaining the pattern of slow recoveries of output: what would be the recovery of output after the last three recessions if consumption recovered at its pre-1990 speed? Figure 3.2 suggests that the recovery of output would have been much stronger at 8.9% instead of 5.6%. The slow recoveries of consumption accounts for 63% of recent slow recoveries of output.[3] The rest of this paper focuses on explaining the recent slow recoveries of consumption and leaves the slow recoveries of output for future research.

This chapter bridges the gap between three strands of the literature, which have not yet been documented in an integrated manner. The first strand concerns routinization and jobless recoveries. The routinization hypothesis of Autor, Levy and Murnane (2003) suggested that computers substitute for routine cognitive occupations, such as clerks and salespeople, and complemented nonroutine cognitive occupations, such as managers and engineers. The first chapter of this dissertation used that hypothesis and the continuous decrease in the price of computers to propose a labor demand explanation for recent changes in the US labor market, such as the shift away from routine occupations and the decline in the labor share of income. Jaimovich and Siu (2012) also used the routinization hypothesis to propose a labor supply explanation for jobless recoveries, when workers quit their routine occupations during the recession and are not ready to take a nonroutine occupation in the recovery. The reallocation from routine to nonroutine occupations can have different types of cost, such as a cost by firms to hire workers in nonroutine occupations (the first chapter of this dissertation) or a retraining period for workers to learn a new job (Jaimovich and Siu, 2012).

[3]See also the report by the Congressional Budget Office, "What accounts for the slow growth of the economy after the Great Recession" of November 2012 for the importance of consumer spending in the weakness of the recovery. See also Parker et al. (2011) for evidence on the effect of the stimulus payments of 2008 on consumer spending.



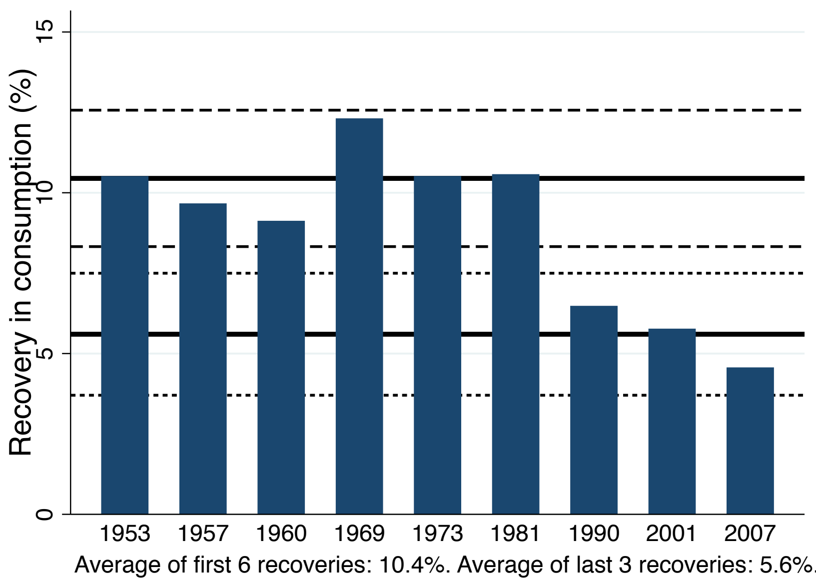


Figure 3.1: Output (top) and consumption (bottom) are slower to recover after recent recessions.

Details: the recovery of quantity X from trough τ is $\log(X_{\tau+2}/X_{\tau})$, between the NBER trough and two years after. Source: Federal Reserve Economic Database. Output is Real GDP and consumption is “Real Personal Consumption Expenditures” (PCECC96). The solid lines in the background are averages and the dashed lines are 95% confidence intervals.

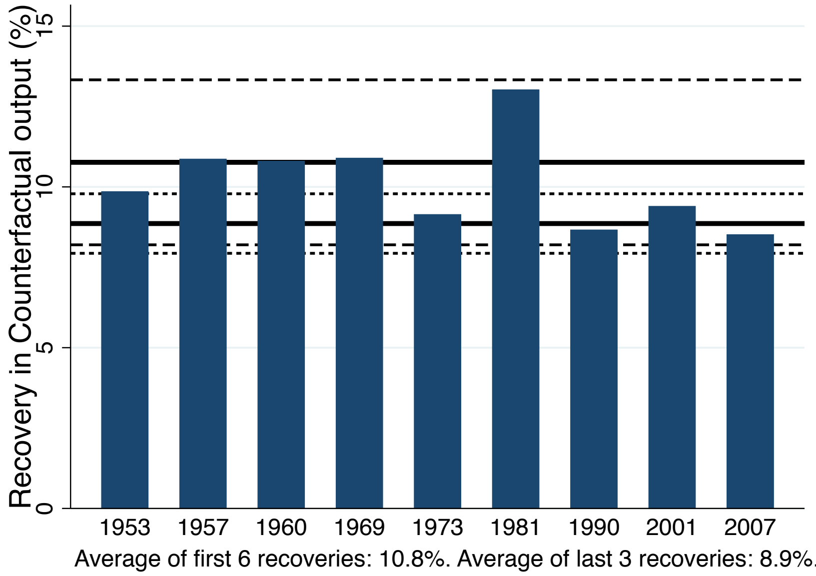


Figure 3.2: The recovery of output would be much stronger if consumption in the last three recessions recovered at the same rate as after the previous 6 recessions.
Details: see text.

The second strand concerns slow recoveries. Galí, Smets and Wouters (2012) documented the different speed of recovery after the recessions of 1990, 2001, and 2007 compared to earlier ones. The speed of recovery of US GDP after recessions in the post-1990 era is twice slower than the pre-1990 era. Figure 3.1 confirms the findings of Galí, Smets and Wouters (2012) for output and extends them to consumption as well. Potential explanations for the different speed of recovery are different shocks and financial frictions, reviewed at the end of the introduction.

The third strand of the literature concerns hand-to-mouth consumption behavior and zero savings. Deaton (1991) proposed an elegant explanation for the empirical regularity that many households save too little. Borrowing constraints give an incentive to hold precautionary savings: a binding borrowing constraint prevents consumption smoothing, so optimizing agents should save more today to prevent the constraint from binding tomorrow. Deaton explains why households save too little by the interaction of borrowing constraints, impatience in consumption, and autocorrelation in the income process.[4] With uncertainty, the impatient household has an incentive to hold precautionary savings but these assets are costly because of foregone current consumption. The borrowing constraint creates an asymmetry in consumption: the household can always save the windfall from a large positive shock but may not be able to borrow to compensate a large negative shock. Higher autocorrelation exacerbates this effect: at the limit of a random walk, a permanent decrease in income leads the household to run down its wealth, which may hit the borrowing constraint. Impatient households with high autocorrelation in income and low initial cash-on-hand can do no better than consume their income. Deaton calls this behavior "simple Keynesian policy" and the subsequent literature refers to it as "hand-to-mouth."[5] Mankiw (2000) used this behavior to propose "the spenders-savers theory of fiscal policy." His model has two types of agents: "savers" are Ramsey agents save their income to smooth consumption; "spenders" are hand-to-mouth agents consume their income. Hand-to-mouth consumption behavior imply that temporary tax changes can affect the demand for goods and services. For example, in 1992, President Bush decreased the federal tax withheld from workers' paychecks without changing the amount owed at the end of the fiscal year. Shapiro and Slemrod (1995) surveyed consumers and found that 43% of respondents would spend most of the extra income.[6] This behavior is incompatible with a model of a representative household able to smooth consumption.

This chapter uses assumptions from these three strands of the literature and asks

[4]If households are sufficiently patient, they have the incentive to save in order to increase consumption in the future, in addition to the precautionary savings motive. Such households would save early in the lifecycle and dissave later. Borrowing constraints are unlikely to bind for these households, which led the author to focus on impatient households.

[5]Such hand-to-mouth behavior is one potential explanation for the excess sensitivity puzzle: consumption responds to predictable changes in income. See Reis (2004) for a review of this literature and another possible explanation with rational inattention.

[6]They asked respondents "How do you think you will use the extra $25 per month—do you think you will spend most of it, save most of it, use most of it to repay debts, or what?"

whether the routinization hypothesis and hand-to-mouth behavior of workers in routine occupations can also explain recent slow recoveries in consumption. It assumes that workers in routine occupations are different from nonroutine occupations in two respects. First, workers in nonroutine occupations are always Ramsey optimizers with smooth consumption whereas workers in routine occupations may be Ramsey optimizers or hand-to-mouth agents (who consume all of their income). Second, employment in nonroutine occupations may grow at the same rate as employment in routine occupations, which corresponds to the US labor market dynamics before the 1980s, or it may grow at a faster rate, which corresponds to the US labor market dynamics after the 1980s. Workers transitioning from routine to nonroutine occupations need to go through a period of retraining, during which they remain unemployed. Workers fired from routine occupations have a high job finding rate before the 1980s and a low job finding rate after the 1980s.

The paper examines the behavior of consumption under four specifications, resulting from turning these two differences on and off. When workers in routine occupations are hand-to-mouth consumers, recoveries of consumption are fast before the 1980s and slow after the 1980s. Workers fired from routine jobs before the 1980s can easily find a new job, so their consumption "bounces back" and recovers back to peak levels. The fast recovery of consumption among routine occupations causes the growth rate of total consumption to be higher than the growth rate of consumption among nonroutine occupations. Workers fired from routine jobs after the 1980s have to go through a period of retraining, during which they consume their unemployment benefits. If these benefits are constant, consumption of workers in retraining is stagnant and the growth rate of total consumption is lower, leading to a slow recovery.

When workers in routine occupations are Ramsey optimizers instead of hand-to-mouth consumers, they are able to smooth consumption growth through job loss, before or after the 1980s. Forward-looking and optimizing workers save to maintain consumption growth during the retraining period.

This chapter also uses the Survey of Consumer Finances to document that households in routine occupations are more credit-constrained than households in nonroutine occupations, which supports the assumption of hand-to-mouth behavior. Future research could micro-found the different behavior of workers in routine and nonroutine occupations with different patience and access to credit markets by occupation. The assumption of hand-to-mouth behavior is also consistent with Stephens (2014), who examines the Health and Retirement Survey and finds that household food consumption "falls by roughly 16% upon being displaced." This result holds even if households anticipate their job displacement and the subsequent fall in earnings. Consumption smoothing is incompatible with the effects of anticipated income shocks on consumption.

Related literature. Current explanations for slow recoveries consist of different shocks or financial frictions. Galí, Smets and Wouters (2012) conclude that recent slow recoveries are due to unusually bad shocks. They estimate a new Keynesian, Dynamic Stochastic General Equilibrium model for the period 1966-2007. They find that risk premium shocks and investment-specific technology shocks have changed in recent recoveries:

> Demand shocks make a large positive contribution to the recoveries of the pre-1990 period, but negative in the post-1990 one. The difference between the two is highly significant, both economically and statistically. This is in itself more than sufficient to explain the difference in recovery growth rates across subsample periods. Investment-specific technology shocks play the largest role in accounting for that difference.

They also estimate the model separately before and after 1984 and they find it "difficult to conclude whether these parameter changes really represent structural changes in the economy or whether they just reflect weak identification." Future research could bridge the gap between this chapter and Galí, Smets and Wouters (2012) by re-estimating their

DSGE model with a trend break in the markup shock. The wage markup in the model of the first chapter of the dissertation has an increasing trend during the phase of technological upgrading: it is the ratio of average labor productivity over the wage, so it equals the inverse of the labor share of income, which the first chapter showed to have a decreasing trend. Estimating such a model may explain the different behavior of shocks in the estimated model of Galí, Smets and Wouters (2012).

On the ability of financial frictions to explain slow recoveries, the literature has not yet reached a consensus. On the one hand, Kannan (2012) correlates exposure to financial frictions to sluggish recoveries from recessions at the sector-level. The dataset consists of aggregate-level data from OECD countries to date business cycles and disaggregate-level data for 28 manufacturing sectors that differ in their reliance on external finance, both covering the period from 1970 to 2003. He finds that sectors relying more on external finance—and more exposed to financial frictions—recover more slowly after recessions. This result is robust to alternative definitions of exposure to financial frictions, such as having fewer assets eligible as collateral or having smaller firms. The effects of financial frictions are strongest in the first year and die out after three years.

On the other hand, Bordo and Haubrich (2011) examine the 27 recessions and recoveries in the United States since 1882 and find that financial crises are generally associated with fast recoveries, though this relationship is not valid for all recessions. They mention that "the evidence for a robust bounce-back is stronger for cycles with financial crises than those without." But three notable exceptions to this pattern are the recessions of 1929, 1990, and 2007.

3.2 A model of slow recoveries in consumption

Time is indexed as $t = 1, 2, \ldots$. The economy has a continuum of workers indexed by $i \in [0, 1]$. These workers are identical except for their occupation: a fraction π_R have routine occupations and $1 - \pi_R$ have nonroutine occupations. For clarity, quantity X for worker i is denoted $X_{NR,i}$ if worker i has a nonroutine occupation and $X_{R,i}$ if worker i has a routine occupation.

The economy is a partial equilibrium model of the demand for consumption, conditional on exogenous processes for employment, wages, and income. The path for these variables could be derived as the result of an inelastic labor supply and a labor demand for both types of occupations from firms, as in the first chapter. This chapter examines the behavior of the economy when an aggregate and unexpected employment shock causes job loss among routine and nonroutine occupations, depending on the labor market dynamics and the behavior of consumption and savings.

3.2.1 Workers in nonroutine occupations

Workers in nonroutine occupations are Ramsey agents and maximize expected utility from consumption $C_{NR,i,t}$:

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t \log \left(C_{NR,i,t} \right),$$

subject to a budget constraint in each period:

$$C_{NR,i,t} + A_{NR,i,t+1} \leq Y_{NR,i,t} + (1 + r) A_{NR,i,t},$$

where $A_{NR,i,t}$ are the assets of the household at the beginning of period t. These assets give the household principal plus interest at the beginning of period t.

Workers in nonroutine occupations have a borrowing constraint:

$$A_{NR,i,t} \geq 0.$$

Workers in nonroutine occupations may be employed or unemployed at time t, with $L_{NR,i,t} \in \{E, U\}$. Employment status is a Markov process with the probability of remaining in employment state $L_{NR,i,t}$ being $p_{NR,s} = \mathbb{P}\left(L_{NR,i,t+1} = s | L_{NR,i,t} = s\right)$ for $s \in \{E, U\}$.

Workers in nonroutine occupations obtain income $Y_{NR,E}$ if employed and unemployment insurance $Y_{NR,U}$ if unemployed.

Households in nonroutine occupations have two state variables at time t: savings and employment status. The Bellman formulation for the household employed in a nonroutine occupation is

$$\begin{aligned} V_{NR,E}\left(A_{NR,i,t}\right) = \max_{C_{NR,i,t}} \Big\{ & \log\left(C_{NR,i,t}\right) \\ & + \beta\, p_E\, V_{NR,E}\left(Y_{NR,E} + (1+r)\, A_{NR,i,t} - C_{NR,i,t}\right) \\ & + \beta\, (1 - p_E)\, V_{NR,U}\left(Y_{NR,U} + (1+r)\, A_{NR,i,t} - C_{NR,i,t}\right) \Big\}. \end{aligned}$$

The Bellman formulation for the unemployed household looking for a nonroutine occupation is similar, replacing the index E with U and vice-versa.

The Bellman formulation has a constraint:

$$Y_{NR,i,t} + (1+r)\, A_{NR,i,t} - C_{NR,i,t} \geq 0.$$

3.2.2 Workers in routine occupations

Workers in routine occupations can also be Ramsey agents, with the same equations as above, or hand-to-mouth consumers. Hand-to-mouth consumers simply consuming all of their income:

$$C_{R,i,t} = Y_{R,i,t}.$$

Workers in routine occupations may be employed or unemployed at time t, with $L_{R,i,t} \in \{0,1\}$. The probability of remaining employed in a routine occupation is denoted $p_{R,E} = \mathbb{P}\left(L_{R,i,t+1} = E | L_{R,i,t} = E\right)$. In the specification before the 1980s, a worker laid off from a routine job can find a routine job right after with probability $1 - p_{R,U}$. In the specification after the 1980s, a worker laid off from a routine job needs to spend τ periods in retraining, after which he finds a nonroutine job with the unconditional probability of being employed in a nonroutine occupation:[7]

$$f_{NR,E} = \left(1 - p_{NR,U}\right) / \left(2 - p_{NR,E} - p_{NR,U}\right).$$

After the transition period, the household that started in a routine occupation has the same employment dynamics as those in nonroutine occupations. The household faces uncertainty on the routine job, no uncertainty in unemployment, and uncertainty again on the nonroutine job.

If workers in routine occupations are Ramsey agents, they follow an optimization problem that takes into account the reallocation into nonroutine occupations after τ periods. Workers in routine occupations have three state variables: employment status, savings, and duration of unemployment if applicable. The Bellman formulation for the household

[7]The vector $(f_{NR,E}, 1 - f_{NR,E})$ is also the eigenvector associated with the eigenvalue 1 for the transition matrix $(p_{NR,E}, 1 - p_{NR,U}; 1 - p_{NR,E}, p_{NR,U})$.

employed in a routine occupation is

$$\begin{aligned}V_{R,E}\left(A_{R,i,t}\right) = \max_{C_{R,i,t}}\Big\{ & \log\left(C_{R,i,t}\right) \\ & + \beta\, p_{R,E}\, V_{R,E}\left(Y_{R,E} + (1+r)\, A_{R,i,t} - C_{R,i,t}\right) \\ & + \beta\left(1 - p_{R,E}\right) V_{R,U}\left(Y_{R,U} + (1+r)\, A_{R,i,t} - C_{R,i,t}\right)\Big\}\end{aligned}$$

The Bellman formulation for a worker fired from a routine job and starting retraining at period t is:[8]

$$\begin{aligned}V_{R,U}\left(A_{R,i,t}\right) = \max_{\left\{C_{R,i,t+s}\right\}}\Bigg\{ & \sum_{s=0}^{\tau-1} \beta^{s} \log\left(C_{R,i,t+s}\right) \\ & + \beta^{\tau}\left[f_{NR,E} V_{NR,E}\left(A_{R,i,t+\tau}\right) + \left(1 - f_{NR,E}\right) V_{NR,U}\left(A_{R,i,t+\tau}\right)\right]\Bigg\},\end{aligned}$$

subject to the intertemporal budget constraint between times t and $t+\tau-d$:

$$\frac{A_{R,i,t+\tau-d}}{(1+r)^{\tau-d-1}} + \sum_{s=0}^{\tau-d-1} \frac{C_{R,i,t+s}}{(1+r)^{s}} \leq (1+r)\, A_{R,i,t} + \sum_{s=0}^{\tau-d-1} \frac{Y_{R,U}}{(1+r)^{s}}.$$

3.2.3 Impulse response functions

This section solves the model numerically and presents four impulse response functions to an unexpected employment shock. The four specifications correspond to the assumptions for workers in routine occupations—Ramsey agents or hand-to-mouth consumers—and for labor market dynamics—before the 1980s with a high job finding rate or after the 1980s with a low job finding rate.

The calibration of the model uses a discount factor $\beta = 0.96 \approx 0.99^{4}$ and an interest rate

[8]The model has perfect foresight during retraining so I define only the value function upon entering retraining and not during retraining.

$r = 5\%$, so the growth rate of consumption with perfect foresight would be $\beta(1+r) - 1 = 0.9\%$. The initial proportion of workers in routine occupations is $\pi_R = 43\%$ and the discount of routine wages compared to nonroutine wages is 46%.[9] Unemployment benefits are 50% of previous income, wether routine or nonroutine income (Nickell, 1997, page 61). Initial wealth of households is three times their current income if they are Ramsey optimizers. For simplicity, the transition probabilities are the same for both workers: $p_{NR,E} = p_{R,E} = p_E$ and $p_{NR,U} = p_{R,U} = p_U$. The probability of remaining unemployed is $p_U = 0.2$, the estimate of Shimer (2008, Figure 1) from the Current Population Survey. The probability of remaining employed is $p_E = 0.95$, the estimate of von Wachter, Song and Manchester (2007, Figure 1A) from Social Security Administrative Data. After the 1980s, a worker laid off from a routine job remains unemployed with probability 1 during retraining, which lasts $\tau = 2$ periods.

The shock in period $t = 5$ is an unexpected job loss, which is four times higher than usual with $\tilde{p}_E = 1 - 4 \times (1 - p_E)$, and an unexpected job finding rate, which is zero with $\tilde{p}_U = 1$.

Figure 3.3 plots the impulse response functions to a negative employment shock before the 1980s. The top panels show that employment in routine and nonroutine occupations behaves similarly and recovers right after the shock. The middle left panel shows that hand-to-mouth consumers decrease consumption upon impact and increase consumption when returning to their jobs. The middle right panel shows that Ramsey workers in routine occupations use their savings to smooth consumption during job loss. The bottom panels plot the behavior of total consumption in logarithms. Consumption "bounces back" in the recovery if workers in routine occupations are hand-to-mouth but is smooth if they are Ramsey optimizers.

[9] Both numbers come from the Current Population Survey for March 2007 defining routine and nonroutine occupations as in section 3.3.

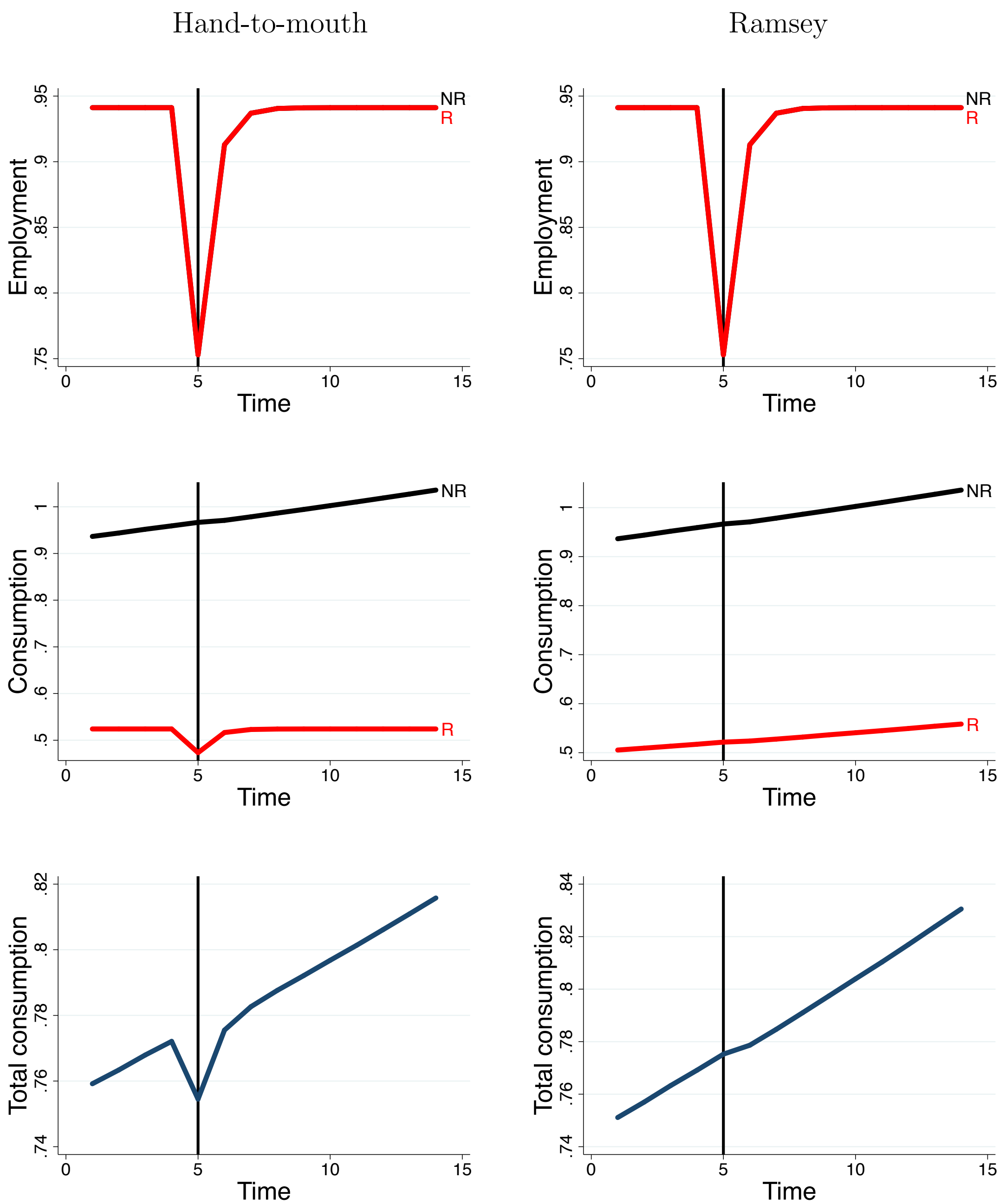


Figure 3.3: The model before the 1980s predicts a fast recovery of consumption if workers in routine occupations are hand-to-mouth consumers and a smooth path of consumption if they are Ramsey agents.

Details: Impulse response functions to a negative employment shock before the 1980s. Path of employment by initial occupation (top), consumption by initial occupation (middle), and total consumption (bottom). Workers in routine occupations as hand-to-mouth consumers (left) or Ramsey optimizers (right).

Figure 3.4 plots the impulse response functions to a negative employment shock after the 1980s. The left panels consider workers in routine occupations as hand-to-mouth consumers and the right panels consider workers in routine occupations as Ramsey optimizers. The top panels plot the path of employment: this path is exogenous and is the same for hand-to-mouth or Ramsey consumers. Employment of households who start in routine occupations declines abruptly in period 5 and remains depressed for $\tau = 2$ periods of retraining. The growth in employment of households initially in routine occupations between periods 5 and 6 comes from the trend of job loss before the shock, which is due to $p_{R,E} < 1$.

The left middle panel plots the response of consumption for hand-to-mouth consumers: they decrease consumption upon impact, maintain low consumption during retraining, and increase consumption when finding the new job. The right middle panel plots the response of consumption for Ramsey consumers: they are able to draw down on savings, so consumption is smooth. The bottom panels plot the behavior of total consumption in logarithms. With hand-to-mouth workers in routine occupations, consumption dips upon impact and takes τ periods to "bounce-back." With Ramsey consumers, consumption growth is smooth: it does not fall in the recession and does not increase much in the recovery.

Table 3.1 summarizes the dynamics of consumption depending on the labor market dynamics and on the consumption behavior for workers in routine occupations. The recovery of consumption after the recession is half as strong in late recessions compared to earlier ones. Hand-to-mouth behavior is crucial for this result: with optimizing Ramsey behavior, all households are able to smooth consumption, whose growth is *higher* for recent recessions compared to previous ones. If households initially in routine occupations optimize, the period of retraining is good news for workers in routine occupations: for a low cost of $\tau = 2$ periods of retraining with half pay, they obtain permanently higher labor income thereafter. With these parameters, consumption increases for workers in routine

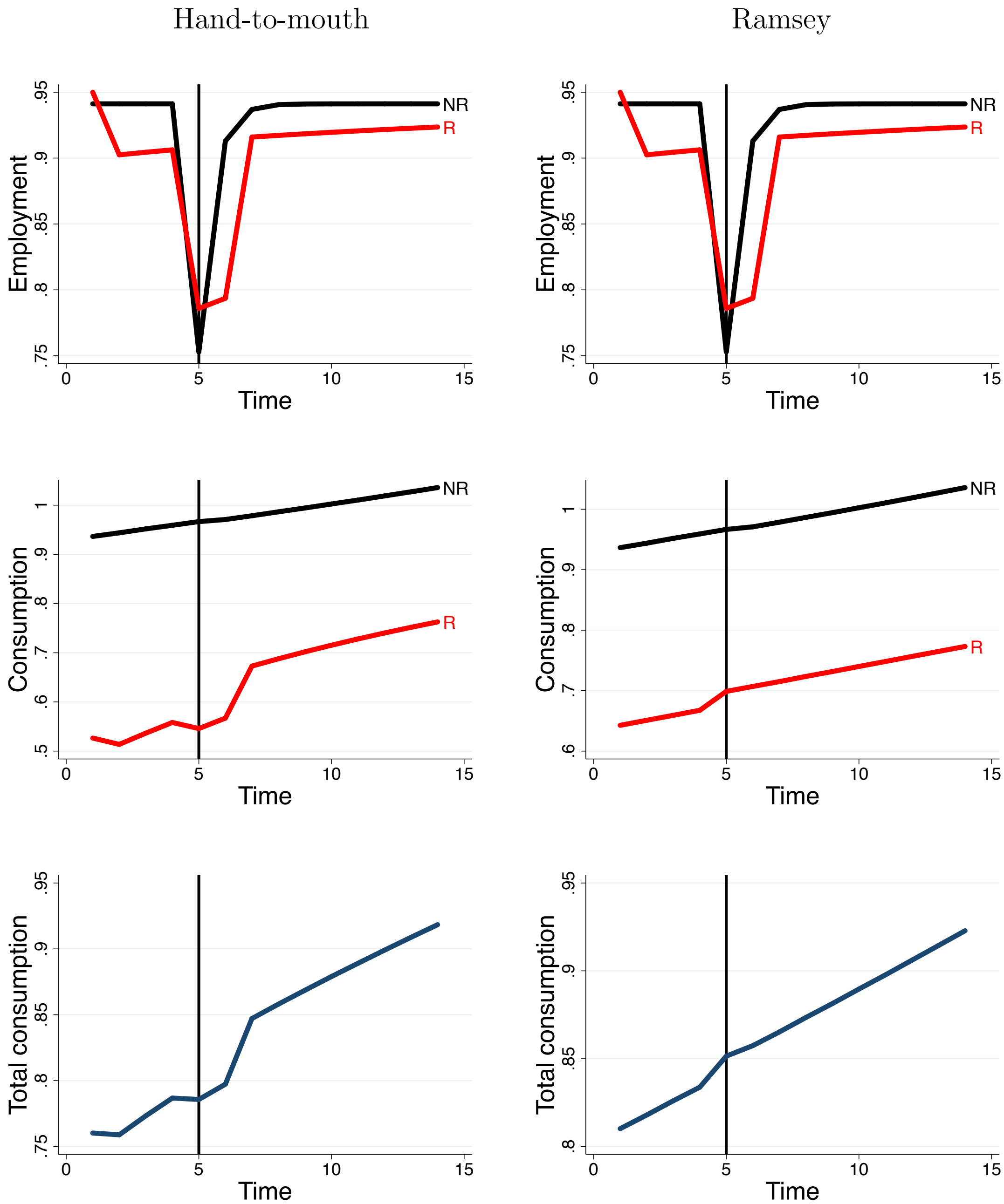


Figure 3.4: The model after the 1980s predicts a slow recovery of consumption if workers in routine occupations are hand-to-mouth consumers and a smooth path of consumption if they are Ramsey agents.

Details: Impulse response functions to a negative employment shock after the 1980s. Path of employment by initial occupation (top), consumption by initial occupation (middle), and total consumption (bottom). Workers in routine occupations as hand-to-mouth consumers (left) or Ramsey optimizers (right).

	Hand-to-mouth households in routine occupations	Ramsey households in routine occupations
Before 1980s (no retraining)	dip and immediate recovery $g_{C,recovery} = 2.8\%$	smooth $g_{C,recovery} = 0.4\%$
After 1980s (with retraining)	dip and delayed recovery $g_{C,recovery} = 1.5\%$	smooth $g_{C,recovery} = 0.7\%$

Table 3.1: Summary of consumption dynamics: if workers in routine occupations are hand-to-mouth agents, consumption is slower to recover after the 1980s compared to before the 1980s.

occupations who become unemployed.

The mechanism in the model is simple. In early recessions, workers fired from routine occupations find a job right after the recession. If workers in routine occupations are hand-to-mouth, they consume their unemployment benefits or their labor income. The increase of employment in routine occupations back to the unconditional distribution causes a fast recovery of consumption after the recession. If workers in routine occupations are optimizers, all households use their savings to smooth consumption—a smooth recovery.

In late recessions, workers switching from a routine to a nonroutine job have to go through retraining. They have constant labor income and face no uncertainty during unemployment. If these workers are hand-to-mouth consumers, they consume all their unemployment benefits. Constant benefits imply constant consumption—a slow recovery:

$$C_{R,i,t} = Y_{R,U}.$$

If these workers are optimizers, they follow the Euler equation with perfect foresight and consumption grows at gross rate $\beta\,(1+r)$—a smooth recovery:

$$\frac{U'\left(C_{R,i,t}\right)}{U'\left(C_{R,i,t+1}\right)} = \frac{C_{R,i,t+1}}{C_{R,i,t}} = \beta\,(1+r)\,.$$

In summary, optimizing behavior for workers in routine occupations implies smooth consumption growth around $\beta(1+r)-1$, before or after the 1980s. Hand-to-mouth behavior implies fast consumption growth before the 1980s and slow consumption growth after the 1980s.

3.3 Data on credit constraints and consumption behavior by occupation

This section presents support for the model by documenting the patterns of on credit constraints and hand-to-mouth behavior by occupation from the Survey of Consumer Finances. It also tests one prediction of the model for durables and nondurables with aggregate-level data.

The Federal Reserve Board sponsored the Survey of Consumer Finances every three years since 1983. It reports financial variables and broad occupation categories from the Census Bureau. In 1983 and from 1989 to 2010, the survey asks respondents about their access to credit. From 1995 to 2010, the survey asks respondents about their consumption behavior. The questions are:

1. "In the past five years, has a particular lender or creditor turned down any request you (or your [husband/wife]) made for credit, or not given you as much credit as you applied for?"

2. "Were you later able to obtain the full amount you (or your husband/wife) requested by reapplying to the same institution or by applying elsewhere?"

3. "Was there any time in the past five years that you (or your [husband/wife]) thought of applying for credit at a particular place, but changed your mind because you thought you might be turned down?"

4. “Over the past year, would you say that (your/your family’s) spending exceeded (your/your family’s) income, that it was about the same as your income, or that you spent less than your income? (Spending should not include any investments you have made.)”

Following Dogra and Gorbachev (2013), I define a household as liquidity constrained if an application for credit was rejected, if it did not obtain the full amount, or if it was too discouraged to apply (i.e., if it answers “yes” to question 1 and “no” to question 2, or if it answers “yes” to question 3). I define a household as having hand-to-mouth behavior if it answers “spending was about the same as income” to question 4.

The Survey of Consumer Finances also reports occupations by broad categories. Acemoglu and Autor (2011) mapped these broad categories into nonroutine jobs (“managerial and professional specialty occupations”) and routine jobs (“technical, sales, and administrative support occupations”). The remaining categories are manual occupations, which Autor, Levy and Murnane (2003) showed to have limited scope for substitutability or complementarity with computers: “service occupations and armed forces,” “precision production, craft, and repair occupations,” “operators, fabricators, and laborers,” and “farming, forestry, and fishing occupations.” Nonroutine jobs represent 44 million households in 2010 and routine jobs represent 22 million households, among 118 million households covered in the survey (the remaining households have manual occupations).

The survey is a repeated cross-section with two sampling schemes: a standard sample from the 48 contiguous US states and a list sample designed to oversample wealthy households. The survey provides sampling weights to correct for the sample design. The aggregate-level figures in this chapter account for these sampling weights.

From 1989 onward, the Survey of Consumers Finances provides five “implicates” for each household. If a variable is missing, each implicate provides a possibly different value for the variable depending on the imputation method. If a variable is not missing, all

Dependent variable	Nonroutine	Routine
Annual income (thousand $)	990	294
Age	52	49
Married	71%	51%
Female	15%	34%
Black	5%	11%
Unemployed	0%	1%
Liquidity constraint	12%	21%
Hand-to-mouth behavior	23%	34%

Table 3.2: Households in routine occupations earn less, are more liquidity-constrained, and are more likely to have hand-to-mouth behavior.
Source: Survey of Consumer Finances.

implicates are the same. I average all implicates by household, except for the occupation category, for which I choose the mode across the five implicates.

Table 3.2 presents summary statistics by occupation for all years. The oversampling of wealthy families implies larges values for annual income of routine and nonroutine occupations. Routine occupations earn three times less than nonroutine, are more likely to be liquidity-constrained, and more likely to spend their income.

Figure 3.5 aggregates across all respondents with their sampling weights. The top panel shows that workers in routine occupations are more likely to be credit-constrained than in nonroutine occupations, from 1983 to 2010. Two alternative measures of credit constraints include credit cards and credit lines and produce similar results. The bottom panel shows that workers in routine occupations are more likely to have hand-to-mouth behavior than workers in nonroutine occupations, from 1995 to 2010.

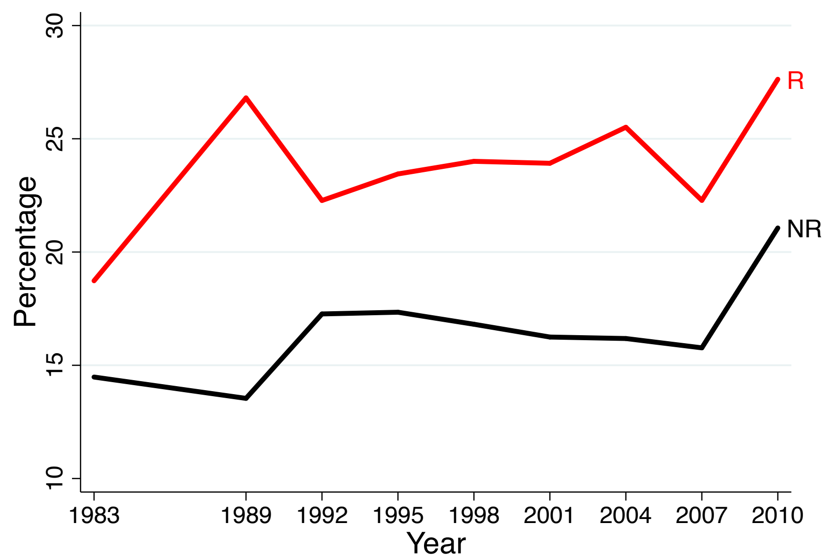
Table 3.3 confirms these results with a regression analysis at the micro-level. Households in routine occupations are more likely to be liquidity constrained and have hand-to-mouth behavior, after controlling for income and demographic characteristics. The estimates are statistically significant at the 5% level. They imply that changing from a routine to a nonroutine occupations makes a households 3 percentage points less likely to be liquidity constrained and to have hand-to-mouth behavior.

Finally, one prediction of this theory that can be tested at the aggregate-level is that the recovery of consumption is slower for durables than for non-durables. Browning and Crossley (2009, page 1175) found that Canadian households respond to a temporary loss of income by "cutting back dramatically on durables and leaving non-durables almost untouched." Figure 3.6 shows that this prediction holds: the recovery of durables purchase is much weaker after the last three recession (4.5% versus 17%), as opposed to a strong recovery in non-durables consumption.

3.4 Conclusion

This chapter explains recent slow recoveries of consumption by assuming that workers in routine occupations have hand-to-mouth consumption behavior. Before the 1980s, these workers were fired in the recession and hired back in the recovery, so the drop in consumption during the recession was followed by a bounce-back in the recovery. After the 1980s, these workers are fired in the recession and need to spend some time in retraining to find a new job, so the drop in consumption during the recession is not followed by a bounce-back in the recovery. A simulation of the model suggests that the recovery of consumption is half as strong after the 1980s compared to before the 1980s, a reduction that is similar to that in the data of Figure 3.1.

The partial equilibrium model in this chapter endogeneizes consumption but output is exogenous to the model. Future research could explain slow recoveries in output by extending the model into a general equilibrium framework and considering the possibility that workers fired from routine jobs may be too discouraged to retrain: as of March 2014,



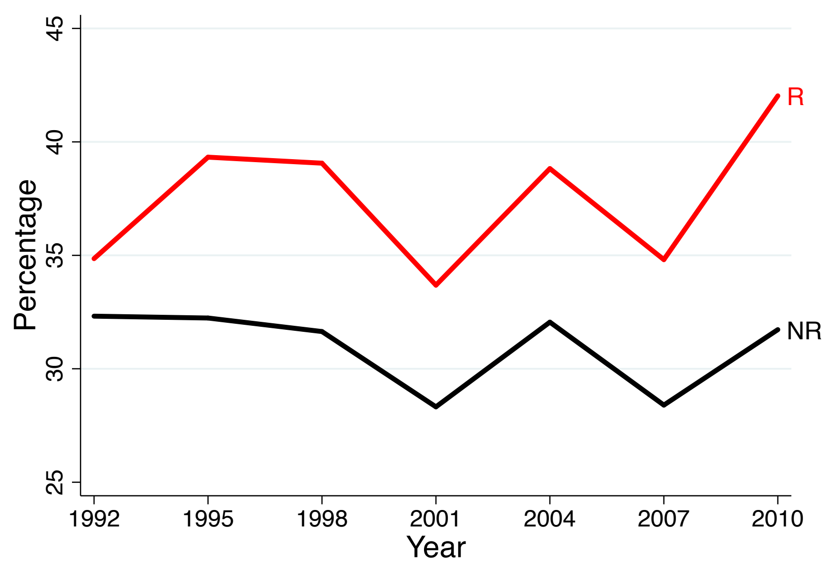


Figure 3.5: Households in routine occupations are more liquidity constrained (top) and more likely to have hand-to-mouth behavior (bottom) than those in nonroutine occupations. Source: Survey of Consumer Finances.

Dependent variable	Liquidity constrained	Hand-to-mouth
routine occupation	0.180*** (0.0429)	0.120*** (0.0367)
log (income)	-0.440*** (0.0208)	-0.467*** (0.0156)
age	0.0575*** (0.00943)	0.00183 (0.00647)
age squared	-0.00107*** (0.000100)	-7.97E-05 (6.04e-05)
married	-0.314*** (0.0558)	0.136*** (0.0492)
female	0.0673 (0.0586)	0.123** (0.0538)
black	0.847*** (0.0600)	0.0217 (0.0607)
unemployed	0.671*** (0.258)	-0.321 (0.458)
Constant	2.315*** (0.262)	4.029*** (0.208)
Observations	23,840	20,515

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3.3: Households in routine occupations are more likely to be liquidity-constrained and have hand-to-mouth behavior, compared to households in nonroutine occupations and controlling for demographic characteristics, in a logit regression including year dummies.

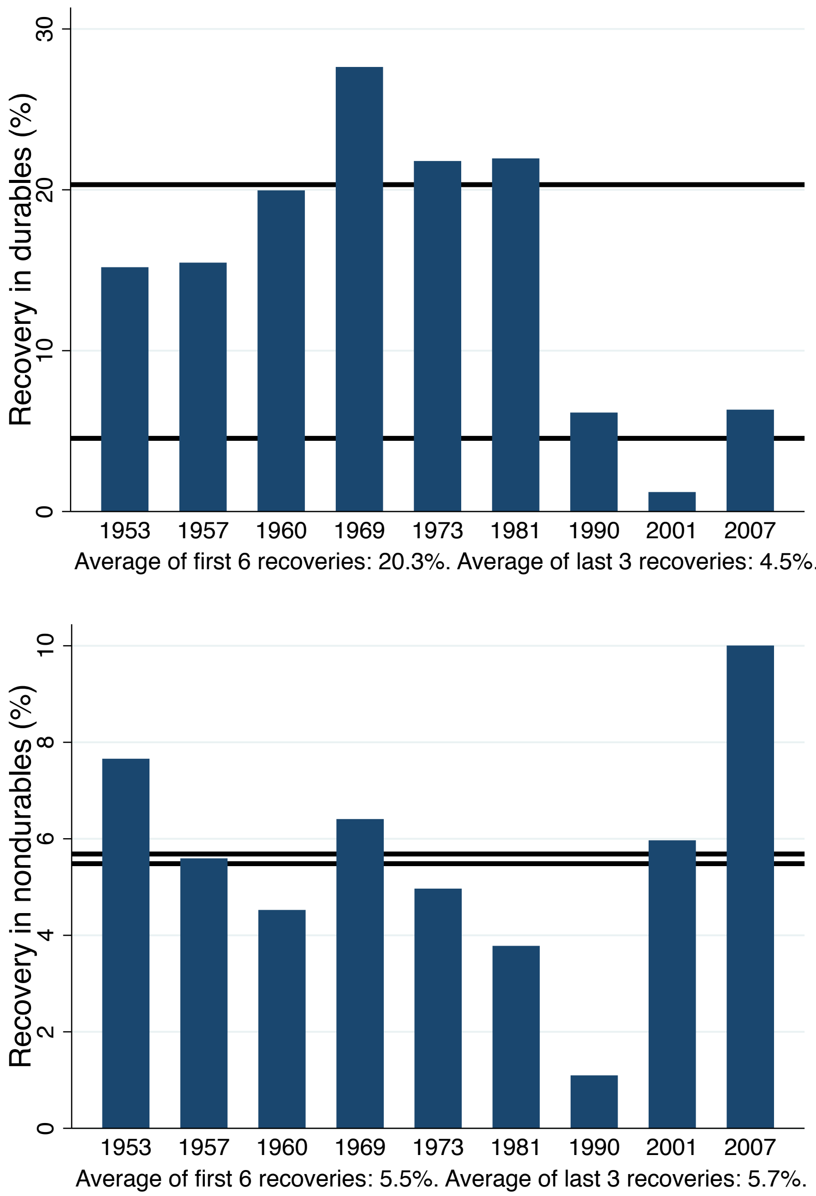


Figure 3.6: The recovery of durable consumption (top) is weaker than that of nondurable consumption (bottom).

Source: Federal Reserve Economic Database, series PCND and PCDG, multiplied by the ratio of PCECC96 to PCEC.

800 thousand workers have searched for jobs but dropped out of the labor force because of discouragement.[10] This discouragement would also reduce output in the long term. Yet another extension to explain slow recoveries in output could include a multiplier effect of consumption on output and employment. The slow recovery of consumption would decrease aggregate demand, production, job creation and labor income, which would further depress consumption in a vicious circle.

[10]Federal Reserve Economic Database, series LNU05026646 and LNU05026647.

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Appendix A

Appendix to Chapter 1

A.1 Equilibrium of the model

Denote $\nu_{C,t}$ and $\nu_{NC,t}$ the Lagrange multipliers of the capital accumulation constraints (equations 1.2.2 and 1.2.3), and μ_t the multiplier of the budget constraint (equation 1.2.4). Denote $H_{NR,t}$ and $H_{R,t}$ the hiring of nonroutine and routine jobs, with constraints:

$$L_{J,t+1} \leq L_{J,t} + H_{J,t}, \qquad H_{J,t} \geq 0, \qquad J = NR, R. \tag{A.1.1}$$

The first constraint implies that increases in employment have to come from hiring. The second constraint implies that hiring is never negative. (If hiring could be negative, the firm would receive subsidies for firing workers.) Denote $\psi_{J,t}$ the multiplier on the first constraint and $\vartheta_{J,t}$ the multiplier on the second constraint. Denote $\iota_{C,t}$ and $\iota_{NC,t}$ the multipliers on the positivity constraint for investment:

$$I_{C,t} \geq 0, \quad I_{NC,t} \geq 0.$$

The first-order conditions of the household's program are:

$$\begin{aligned}
\left(C_t - X_t \frac{\varepsilon}{1+\varepsilon} L_t^{\frac{1+\varepsilon}{\varepsilon}}\right)^{-1} &= \mu_t \\
X_t L_t^{\frac{1}{\varepsilon}} &= w_t \\
\mu_t r_{NC,t} &= \theta^{-1} \nu_{NC,t-1} - \nu_{NC,t} \left(1 - \delta_{NC}\right) \\
\mu_t r_{C,t} &= \theta^{-1} \nu_{C,t-1} - \nu_{C,t} \left(1 - \delta_{C}\right) \\
\nu_{NC,t} &= \mu_t - \iota_{NC,t} \\
\nu_{C,t} &= \mu_t \exp\left(-b_t\right) - \iota_{C,t}
\end{aligned}$$

The household's subjective discount factor, inherited by the firm, is

$$D_{0,t} = \theta^t \frac{\mu_t}{\mu_0}.$$

The household's program has four complementarity slackness conditions:

$$\begin{aligned}
0 &= I_{NC,t} \iota_{NC,t}, \\
0 &= I_{C,t} \iota_{C,t}, \\
0 &= \nu_{NC,t} \left(\left(1 - \delta_{NC}\right) K_{NC,t} + I_{NC,t} - K_{NC,t+1}\right), \\
0 &= \nu_{C,t} \left(\left(1 - \delta_{C}\right) K_{C,t} + I_{C,t} - K_{C,t+1}\right).
\end{aligned}$$

For ease of notation, this appendix uses $\rho = \left(\sigma - 1\right)/\sigma$. The first-order conditions of the firm imply:

$$MPL_{NR,t} = \beta A_t K_{NC,t}^{\alpha} L_{NR,t}^{\beta-1} \left(K_{C,t}^{\rho} + L_{R,t}^{\rho}\right)^{\gamma/\rho} = w_t + \frac{D_{0,t-1}}{D_{0,t}} \psi_{NR,t-1} - \psi_{NR,t},$$
$$MPL_{R,t} = \gamma A_t K_{NC,t}^{\alpha} L_{R,t}^{\rho-1} L_{NR,t}^{\beta} \left(K_{C,t}^{\rho} + L_{R,t}^{\rho}\right)^{\frac{\gamma}{\rho}-1} = w_t + \frac{D_{0,t-1}}{D_{0,t}} \psi_{R,t-1} - \psi_{R,t},$$
$$MPK_{NC,t} = \alpha A_t K_{NC,t}^{\alpha-1} L_{NR,t}^{\beta} \left(K_{C,t}^{\rho} + L_{R,t}^{\rho}\right)^{\gamma/\rho} = r_{NC,t},$$
$$MPK_{C,t} = \gamma A_t K_{C,t}^{\rho-1} K_{NC,t}^{\alpha} L_{NR,t}^{\beta} \left(K_{C,t}^{\rho} + L_{R,t}^{\rho}\right)^{\frac{\gamma}{\rho}-1} = r_{C,t},$$
$$\vartheta_{NR,t} = c_{NR} - \psi_{NR,t},$$
$$\vartheta_{R,t} = c_{R} - \psi_{R,t},$$

where MPF is the marginal product of factor F. The firm makes zero intertemporal profits but it may make positive or negative profits in each period, reverted to or financed by the household.

The firm's program has two complementarity slackness conditions:

$$\vartheta_{NR,t} H_{NR,t} = \psi_{NR,t} \left(L_{NR,t} + H_{NR,t} - L_{NR,t+1}\right) = 0,$$

$$\vartheta_{R,t} H_{R,t} = \psi_{R,t} \left(L_{R,t} + H_{R,t} - L_{R,t+1}\right) = 0.$$

The set of equilibrium conditions also includes the physical constraints of the model (equations 1.2.2-1.2.7) and the following transversality conditions:

$$\lim_{t\to\infty} D_{0,t} K_{NC,t} = \lim_{t\to\infty} D_{0,t} K_{C,t} = 0.$$

For computational reasons, the numerical solution truncates the horizon at $T < \infty$. An equilibrium, solved by AMPL (A Mathematical Programming Language) is a set of $19 \times T$ variables (consumption C_t, capital stocks $K_{C,t}$ and $K_{NC,t}$, investments $I_{C,t}$ and $I_{NC,t}$, employment quantities L_t, $L_{NR,t}$ and $L_{R,t}$, output Y_t, rental rates $r_{C,t}$ and $r_{NC,t}$, wages w_t, Lagrange multipliers $\nu_{C,t}$, $\nu_{NC,t}$, μ_t, $\psi_{NR,t}$, $\vartheta_{NR,t}$, $\iota_{C,t}$, $\iota_{NC,t}$) solving $19 \times T$ equations (capital accumulation constraints (1.2.2-1.2.3), budget constraint (1.2.4), production function (1.2.5), labor market equilibrium (1.2.7), six optimality conditions for the household, five optimality conditions for the firm, and three complementarity slackness conditions).

The numerical solution replaces some of these equations with boundary conditions. Eight equations are intertemporal and involve quantities at times t and $t+1$: the two capital accumulation constraints, the two labor accumulation constraints, the two first-order conditions for the firm on labor, and the two first-order conditions for the household on capital accumulation. The equilibrium has $T-1$ of these equations, with 8 equations missing from the total set. These eight equations are replaced with boundary conditions for the two types of capital and the two types of labor at time 1 and time T, equal to their values in the initial or final steady-state. The steady-state is a set of time-independent variables solving these equations when the outside variables (A_t, b_t, X_t) or (b_t, X_t, Y_t) are fixed at their level at time 1 or time T. To ensure that these boundary conditions play a minimal role, the calibration includes a buffer of 20 time periods at the beginning and 60 time periods at the end, where the outside variables equal their initial or final values, e.g. $A_t = A_1$ for $t \leq 20$ and $b_t = b_T$ for $t \geq T - 60$.

A.2 General proofs

Proof of Lemma 4. Given that this model has no market failures, the market equilibrium coincides with the optimum of a benevolent social planner who maximizes the household's utility:

$$\max \quad \sum_{t=0}^{\infty} \theta^t \log\left(C_t - X_t \frac{\varepsilon}{1+\varepsilon} L_t^{\frac{1+\varepsilon}{\varepsilon}}\right),$$

subject to the physical constraints in equations (1.2.3-1.2.2), (1.2.5-1.2.7), and to the following resource constraint (implied by the definition of profits, the budget constraint, and the labor market equilibrium):

$$Y_t = C_t + I_{NC,t} + \exp\left(-b_t\right) I_{C,t} + c_{NR}\left(L_{NR,t+1} - L_{NR,t}\right)^+ + c_R\left(L_{R,t+1} - L_{R,t}\right)^+ .$$

The Bellman formulation for the planner's problem uses five state variables and seven control variables:

$$V\left(K_{NC,t}, K_{C,t}, L_{NR,t}, L_{R,t}, t\right) = \max_{C_t, H_{NR,t} H_{R,t},, I_{C,t}, I_{NC,t}} \Bigg\{ \log\left(C_t - X_t \frac{\varepsilon}{1+\varepsilon} L_t^{\frac{1+\varepsilon}{\varepsilon}}\right) + \theta V\left(K_{NC,t+1}, K_{C,t+1}, L_{NR,t+1}, L_{R,t+1}, t+1\right)\Bigg\},$$

subject to the same physical constraints.

The contraction mapping for a Bellman operator requires three Blackwell conditions. First, the set of controls is bounded: hiring variables are bounded above by maximum labor supply $\bar{L}$ and quantity variables of consumption and investment are bounded by production Y_t, which is set by the four inputs as state variables. Both the disutility from labor supply and the utility from consumption are bounded. The Bellman operator maps the space of bounded functions into itself.

The remaining two conditions, monotonicity and discounting, follow from the Bellman formulation of the problem with a discount parameter θ. The contraction mapping theorem guarantees existence and uniqueness of the equilibrium of the model Stokey and Lucas (see 1989, page 54).

In one numerical exercise, the hiring cost c_R is zero and employment $L_{R,t}$ in routine occupations is no longer a state variable. The Bellman operator becomes:

$$V\left(K_{NC,t}, K_{C,t}, L_{NR,t}, t\right) = \max_{C_t, H_{NR,t} H_{R,t}, I_{C,t}, I_{NC,t}, L_{R,t}} \left\{ \log\left(C_t - X_t \frac{\varepsilon}{1+\varepsilon} L_t^{\frac{1+\varepsilon}{\varepsilon}}\right) \right.$$
$$\left. + \theta V\left(K_{NC,t+1}, K_{C,t+1}, L_{NR,t+1}, t+1\right) \right\}.$$

Labor variables are still bounded above by maximum labor supply $\bar{L}$ and quantity variables of consumption and investment are bounded above by maximum production $\bar{Y}_t$:

$$\bar{Y}_t = A_t K_{NC,t}^{\alpha} L_{NR,t}^{\beta} \left(K_{C,t}^{\rho} + \left(\bar{L} - L_{NR,t}\right)^{\rho}\right)^{\frac{\gamma}{\rho}},$$

so the three Blackwell conditions still hold and the equilibrium exists.

Proof of Lemma 5. In the limiting balanced growth path, where the capital stocks grow at constant rates, investment is positive and the Lagrange multipliers on investment are zero:

$$\iota_{NC,t} = \iota_{C,t} = 0.$$

The Lagrange multipliers on capital accumulation are linked to the marginal utility μ_t from consumption:

$$\nu_{NC,t} = \mu_t,$$
$$\nu_{C,t} = \mu_t \exp\left(-b_t\right).$$

The equilibrium rental rates of capital are constant:

$$
\begin{aligned}
r_{NC,t} &= \theta^{-1}\frac{\mu_{t-1}}{\mu_t} - 1 + \delta_{NC}, \\
&\rightarrow \theta^{-1}\left(1+g_\mu\right)^{-1} - 1 + \delta_{NC}, \\
r_{C,t} &= \theta^{-1}\frac{\mu_{t-1}}{\mu_t}\exp\left(-b_{t-1}\right) - \exp\left(-b_t\right)\left(1-\delta_C\right), \\
&\rightarrow \exp\left(-\bar{b}\right)\left(\theta^{-1}\left(1+g_\mu\right)^{-1} - 1 + \delta_C\right).
\end{aligned}
$$

The firm's limiting subjective one-period discount factor also converges:

$$
\frac{D_{0,t-1}}{D_{0,t}} = \frac{\mu_{t-1}}{\theta\mu_t} \rightarrow \theta^{-1}\left(1+g_\mu\right)^{-1}.
$$

The factor price frontier, implied by the firm's first-order conditions, is:

$$
\underbrace{\alpha^\alpha\beta^\beta\gamma^\gamma A_t}_{\rightarrow\infty} = r_{NC,t}^\alpha w_t^\beta \tau_{NR,t}^\beta\left(r_{C,t}^{1-\sigma} + w_t^{1-\sigma}\tau_R^{1-\sigma}\right)^{\frac{\gamma}{1-\sigma}}, \qquad \tau_{J,t} = 1 + \frac{D_{0,t-1}}{D_{0,t}}\frac{\psi_{J,t-1}}{w_t} - \frac{\psi_{J,t}}{w_t}.
$$

The left-hand side of the factor price frontier diverges. The wage cannot converge to zero, otherwise the right-hand side of the factor price frontier converges to zero. So the wage is bounded away from zero. On the right-hand side, the two rental rates of capital and the one-period discount factor converge. The multipliers $\left\{\psi_{NR,t}, \psi_{R,t}\right\}$ are bounded between 0 and $\{c_{NR}, c_R\}$, the wage is bounded away from zero, and the one-period discount factor converges, so the terms $\tau_{J,t}$ are bounded. All terms on the right-hand side converge or are bounded, except for wages w_t. Therefore, wages also diverge and grow indefinitely at a rate implied by the limiting factor price frontier:

$$
g_w = \frac{g_A}{\beta}.
$$

Given constant rental rates of capital and unbounded wages, the limiting capital-output ratios are constant:

$$\frac{K_{NC,t}}{Y_t} = \frac{\alpha}{r_{NC,t}} \to \frac{\alpha}{r_{NC}},$$
$$\frac{K_{I,t}}{Y_t} = \frac{\gamma}{r_{C,t}} \left(1 + \left(\frac{w_t}{r_{C,t}}\right)^{1-\sigma}\right)^{-1} \to \frac{\gamma}{r_C}.$$

The labor supply equation from the household is:

$$X_t L_t^{\frac{1}{\varepsilon}} = w_t,$$

For a balanced growth path with constant employment, the growth in the disutility of labor supply has to verify:

$$g_X = g_w = g_A/\beta.$$

As wages grow indefinitely, the relative cost of computer capital decreases to zero and employment reallocates entirely from routine to nonroutine jobs:

$$L_{NR,t} \to L, \qquad L_{R,t} \to 0.$$

The limiting production function is a three-factor Cobb-Douglas:

$$Y_t \to A_t K_{NC,t}^{\alpha} L_{NR,t}^{\beta} K_{I,t}^{\gamma},$$

which implies the following equation between limiting growth rates:

$$g_Y = g_A + \alpha g_{K_{NC}} + \beta g_L + \gamma g_{K_I}.$$

Using the constant capital-output ratios and the limiting growth rate of employment, the growth rate of output is:

$$g_Y = g_A + \alpha g_Y + \gamma g_Y = \frac{g_A}{1-\alpha-\gamma} = \frac{g_A}{\beta}.$$

At the limit, the investment-capital ratios are constant:

$$\frac{I_{J,t}}{K_{J,t}} = \frac{K_{J,t+1}}{K_{J,t}} - (1-\delta_J) \to g_{K_J} + \delta_J = g_Y + \delta_J, \qquad J = C, NC.$$

Therefore, the investment-output ratios are also constant and the two types of investment grow at rate $g_Y = g_A/\beta$. The resource constraint implies that consumption tends to a constant share of output:

$$\begin{aligned}\frac{C_t}{Y_t} &= 1 - \frac{I_{NC,t}}{Y_t} - \exp\left(-b_t\right)\frac{I_{C,t}}{Y_t} \\ &= 1 - \frac{I_{NC,t}}{K_{NC,t}}\frac{K_{NC,t}}{Y_t} - \exp\left(-b_t\right)\frac{I_{C,t}}{K_{C,t}}\frac{K_{C,t}}{Y_t} \\ &\to 1 - \left(\delta_{NC} + \frac{g_A}{\beta}\right)\frac{\alpha}{r_{NC}} - \exp\left(-\bar{b}\right)\left(\delta_C + \frac{g_A}{\beta}\right)\frac{\gamma}{r_C}.\end{aligned}$$

Therefore, consumption grows at the same rate as output, and all quantities grow at the same rate, as well as the wage:

$$g_C = g_Y = g_{K_I} = g_{K_{NC}} = g_{I_I} = g_{I_{NC}} = g_w = \frac{g_A}{\beta}.$$

To prove that the Lagrange multiplier μ_t declines at the same rate g_A/β, note that the labor share of income is:

$$\begin{aligned}\frac{w_t L_t}{Y_t} &= \frac{w_t L_{NR,t}}{Y_t} + \frac{w_t L_{R,t}}{Y_t},\\ &= \left(MPL_{NR,t} + \psi_{NR,t} - \frac{D_{0,t-1}}{D_{0,t}}\psi_{NR,t-1} \right) \frac{L_{NR,t}}{Y_t}\\ &+ \left(MPL_{R,t} + \psi_{R,t} - \frac{D_{0,t-1}}{D_{0,t}}\psi_{R,t-1} \right) \frac{L_{R,t}}{Y_t},\\ &= \beta + \left(\psi_{NR,t} - \frac{D_{0,t-1}}{D_{0,t}}\psi_{NR,t-1} \right) \frac{L_{NR,t}}{Y_t}\\ &+ \gamma \frac{L_{R,t}^{\rho}}{K_{C,t}^{\rho} + L_{R,t}^{\rho}} + \left(\psi_{R,t} - \frac{D_{0,t-1}}{D_{0,t}}\psi_{R,t-1} \right) \frac{L_{R,t}}{Y_t}.\end{aligned}$$

This share converges to β, since the multipliers $\psi_{J,t}$ are bounded, the one-period discount factor converges, employment in nonroutine occupations is bounded, employment in routine occupations tends to zero, and output diverges.

The marginal utility μ_t from consumption multiplied by consumption tends to a constant, so μ_t declines at rate g_A/β:

$$\begin{aligned}\mu_t C_t &= C_t \left(C_t - X_t \frac{\varepsilon}{1+\varepsilon} L_t^{\frac{1+\varepsilon}{\varepsilon}} \right)^{-1}\\ &= \left(1 - \frac{\varepsilon}{1+\varepsilon} \frac{w_t L_t}{C_t} \right)^{-1}\\ &= \left(1 - \frac{\varepsilon}{1+\varepsilon} \frac{w_t L_t}{Y_t} \frac{Y_t}{C_t} \right)^{-1}\\ &\to \left(1 - \beta \frac{\varepsilon}{1+\varepsilon} \left(1 - \left(\delta_{NC} + \frac{g_A}{\beta} \right) \frac{\alpha}{r_{NC}} - \exp\left(-\bar{b}\right) \left(\delta_C + \frac{g_A}{\beta} \right) \frac{\gamma}{r_C} \right)^{-1} \right)^{-1}.\end{aligned}$$

A.3 Proofs in the special case of the model

Proof of Lemma 6. This proof omits the time index t. For the equilibrium condition, note that the resource constraint on the product market and the household's budget constraint imply zero profits for the firm. Denoting Π_j the indexed product operator (different from the logarithm π of labor productivity), consider a multifactor Cobb-Douglas production function, $Y = A \prod_j F_j^{\alpha_j}$, with constant returns to scale $\sum \alpha_j = 1$. Denote the marginal cost of each factor F_j with mc_j. Optimization of this production function implies constant factor shares:

$$F_j = \frac{\alpha_j Y}{mc_j}.$$

Raising to the power α_j and multiplying over j yields:

$$\frac{Y}{A} = \prod_j F_j^{\alpha_j} = \prod_j \left(\frac{\alpha_j}{mc_j}\right)^{\alpha_j} \times \; Y^{\sum \alpha_j} \quad \Longrightarrow \quad \frac{1}{A} \prod_j \left(\frac{mc_j}{\alpha_j}\right)^{\alpha_j} = 1.$$

The marginal cost of the first two factors, K_{NC} and L_{NR}, is 1 and w. The marginal cost of the third Cobb-Douglas factor, the Constant-Elasticity-of-Substitution aggregate, requires more detail. Consider a firm that is selling the third Cobb-Douglas factor at marginal cost mc_3 to maximize profits:

$$\max_{K_C, L_R} \quad mc_3 \, (K_C^\rho + L_R^\rho)^{\frac{1}{\rho}} - r_C \, K_C - w \, L_R.$$

The ratio of first-order conditions on capital K_C and labor L_R imply:

$$\left(\frac{K_C}{L_R}\right)^{\rho - 1} = \frac{r_C}{w} \quad \Rightarrow \quad \frac{K_C}{L_R} = \left(\frac{w}{r_C}\right)^{\sigma}$$

The first-order condition for labor implies:

$$mc_3 \, (K_C^\rho + L_R^\rho)^{\frac{1}{\rho} - 1} \, L_R^{\rho - 1} = w.$$

Rearrange this expression, use $\sigma\rho = \sigma - 1$ and the solution for computer capital relative to employment in routine occupations to obtain:

$$
\begin{aligned}
mc_3 &= \left(1 + \left(\frac{K_C}{L_R}\right)^{\rho}\right)^{1-\frac{1}{\rho}} w \\
&= \left(1 + \left(\frac{w}{r_C}\right)^{\rho\sigma}\right)^{\frac{1}{1-\sigma}} w \\
&= \left(1 + w^{\sigma-1} r_C^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \left(w^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \\
mc_3 &= \left(r_C^{1-\sigma} + w^{1-\sigma}\right)^{\frac{1}{1-\sigma}}
\end{aligned}
$$

The zero profit condition of the three factor Cobb-Douglas production function is

$$
\frac{1}{A}\left(\frac{1}{\alpha}\right)^{\alpha}\left(\frac{w}{\beta}\right)^{\beta}\left(\frac{\left(r_C^{1-\sigma} + w^{1-\sigma}\right)^{\frac{1}{1-\sigma}}}{\gamma}\right)^{\gamma} = 1.
$$

This equation is the equilibrium condition for the wage, where the marginal cost of production equals the marginal revenue. The left-hand side is strictly increasing in w, equals 0 for $w = 0$ and tends to infinity for $w \to \infty$. Therefore, the wage that verifies the equation is unique.

Proof of Proposition 7. The routine share of employment is:

$$
\frac{L_{R,t}}{L_t} = \frac{L_{R,t}}{L_{NR,t} + L_{R,t}} = \left(1 + \frac{L_{NR,t}}{L_{R,t}}\right)^{-1} = \left(1 + \frac{\beta}{\gamma}\frac{r_{C,t}^{1-\sigma} + w_t^{1-\sigma}}{w_t^{1-\sigma}}\right)^{-1},
$$

where the third equality uses the first-order conditions for the firm. At the limit $b_t \to -\infty$, the wage tends to a lower bound $\underline{w}$ pinned down by the factor price frontier. At the limit $b_t \to \infty$, the factor price frontier implies that the wage diverges. The limiting values of the routine share of employment are

$$
\lim_{b_t \to -\infty} \frac{L_{R,t}}{L_t} = \lim_{r_{C,t} \to \infty} \frac{L_{R,t}}{L_t} = \left(1 + \frac{\beta}{\gamma}\right)^{-1} = \frac{\gamma}{\beta + \gamma}, \qquad \lim_{b_t \to \infty} \frac{L_{R,t}}{L_t} = \lim_{r_{C,t} \to 0} \frac{L_{R,t}}{L_t} = 0.
$$

To compute the impact of the change in the price of computers on the routine share of employment, denote $s_t = \log(L_{R,t}/L_t)$ the logarithm of the routine share of employment. The elasticity of the routine share of employment, after accounting for the effect of b_t on the wage, is negative:

$$\frac{\partial s_t}{\partial b_t} = (1-\sigma)\,\beta\,(\beta+\gamma)\,\frac{1+\left(e^{b_t}w_t\right)^{(1-\sigma)}}{\left(\beta+(\beta+\gamma)\,(e^{b_t}w_t)^{(1-\sigma)}\right)^2}.$$

This elasticity is negative: cheaper computers decrease the routine share of employment. The limiting values of the elasticity are:

$$\lim_{b_t\to-\infty}\frac{\partial s_t}{\partial b_t} = 0, \qquad \lim_{b_t\to\infty}\frac{\partial s_t}{\partial b_t} = (1-\sigma)\left(1+\frac{\gamma}{\beta}\right).$$

Proof of Proposition 8. Labor productivity $\pi_t = \log(Y_t/L_t)$ is:

$$\pi_t = \log\frac{w_t}{\beta+\gamma\left(1+r_{C,t}^{1-\sigma}w_t^{\sigma-1}\right)^{-1}}. \tag{A.3.1}$$

where the rental cost of computer capital is $r_{C,t} = \exp(-b_t)$ (see the proof of Proposition 9 for details).

The first derivative of labor productivity with respect to b_t is:

$$\frac{\partial \pi_t}{\partial b_t} = \gamma\frac{\beta+(\beta+\gamma)\,\sigma\left(e^{b_t}w_t\right)^{1-\sigma}}{\left(\beta+(\beta+\gamma)\,(e^{b_t}w_t)^{1-\sigma}\right)^2} \tag{A.3.2}$$

At the limit $b_t \to -\infty$, the wage tends to a finite value $\underline{w}$, which solves the factor price frontier (1.3.1) with $r_{C,t}\to\infty$. The term $\left(e^{b_t}w_t\right)^{1-\sigma}$ tends to infinity. Factoring that term in the numerator and the denominator, the numerator tends to $(\beta+\gamma)\,\sigma$ and the denominator tends to infinity, so the fraction tends to 0. At the limit $b_t\to\infty$, the wage grows arbitrarily large and the term $\left(e^{b_t}w_t\right)^{1-\sigma}$ tends to zero, so the derivative tends to

γ/β.

The second derivative of labor productivity π_t with respect to b_t is:

$$\begin{aligned}\frac{\partial^2 \pi_t}{\partial b_t^2} &= \gamma\left(\sigma-1\right)\left(\beta+\gamma\right)^2\left(e^{b_t}w_t\right)^{2(1-\sigma)}\left(1+\left(e^{b}w\right)^{(\sigma-1)}\right)\\ &\times\left(\beta\left(2-\sigma\right)+\left(e^{b_t}w_t\right)^{1-\sigma}\left(\beta+\gamma\right)\sigma\right)\\ &\times\left(\beta+\left(e^{b_t}w_t\right)^{1-\sigma}\left(\beta+\gamma\right)\right)^{-4}.\end{aligned}$$

For $\sigma \in (1,2]$, all the terms in this expression are strictly positive. For $\sigma > 2$, all the terms are positive, except the second line, which changes signs at b^* verifying:

$$b^* + \log w\left(b^*\right) = \frac{1}{\sigma-1}\log\left(\frac{\sigma}{\sigma-2}\left(1+\frac{\gamma}{\beta}\right)\right).$$

The left-hand side, as a function of b_t, is strictly increasing and has limits at $\pm\infty$ for $b_t \to \pm\infty$, so the equation has one and only one solution b^*.

Proof of Proposition 9. The labor share of income is:

$$\begin{aligned}\frac{w_t L_t}{Y_t} &= \frac{w_t L_{NR,t}}{Y_t} + \frac{w_t L_{R,t}}{Y_t}\\ &= \beta + \gamma\frac{w_t^{\beta+1-\sigma}\left(r_{C,t}^{1-\sigma}+w_t^{1-\sigma}\right)^{\frac{\gamma}{1-\sigma}-1}}{w_t^{\beta}\left(r_{C,t}^{1-\sigma}+w_t^{1-\sigma}\right)^{\frac{\gamma}{1-\sigma}}}\\ &= \beta + \gamma\left(1+\left(\frac{r_{C,t}}{w_t}\right)^{1-\sigma}\right)^{-1}.\end{aligned}$$

The cost $r_{C,t}$ of computer capital decreases with time, while the wage w_t increases with time, so the labor share of income unambiguously decreases with time.

At the limit $b_t \to -\infty$, the rental rate $r_{C,t}$ of computers becomes arbitrarily large while the wage converges to $\underline{w}$, so the labor share of income tends to $\beta+\gamma$. At the limit $b_t \to \infty$, the rental rate $r_{C,t}$ of computers becomes arbitrarily small, the wage becomes arbitrarily large, so the labor share of income tends to β.

Proof of Corollary 10. Take the limit $\sigma \to 1$ in the expressions for the last three proofs.

Proof of Proposition 11. Denote log-employment with $l(t)$, log-output with $y(t)$, and the logarithm of labor productivity with $\pi(t)$:

$$y(t) = \pi(t) + l(t).$$

A linear approximation of employment growth around its trough t_l yields:

$$\dot{l}(t) = \underbrace{\dot{l}(t_l)}_{=0} + (t - t_l)\,\ddot{l}(t_l) + o(t - t_l).$$

Write output growth as productivity growth plus employment growth and use the linear approximation:

$$\dot{y}(t) = \dot{\pi}(t) + \dot{l}(t) = \dot{\pi}(t) + \ddot{l}(t_l)(t - t_l) + o(t - t_l).$$

The trough t_y of output verifies:

$$\dot{y}(t_y) = 0 = \dot{\pi}(t_y) + \ddot{l}(t_l)(t_y - t_l) + o(t_y - t_l) \quad \Leftrightarrow \quad t_l - t_y = \frac{\dot{\pi}(t_y)}{\ddot{l}(t_l)} + o(t_l - t_y).$$

The labor supply equation is:

$$X_t L_t^{\frac{1}{\varepsilon}} = w_t.$$

The wage depends only on the trend of TFP and of the price of computer investment. The trend component of X_t offsets the wage, so employment depends on the cyclical component $\tilde{x}_t$ of the labor supply shifter:

$$L_t \propto \exp\left(\varepsilon\, \tilde{x}_t\right).$$

Since $\tilde{x}_t$ is periodic with a single trough, $\ddot{l}\left(t_l\right)$ is also periodic and has the same value at all troughs, denoted $\ddot{l}_{trough}$. Since labor has a trough, $\ddot{l}_{trough} > 0$. To a first-order approximation, the length of the jobless recovery is proportional to productivity growth $\dot{\pi}$:

$$t_l - t_y \approx \frac{\dot{\pi}\left(t_y\right)}{\ddot{l}_{trough}}.$$

The meaning of the first-order approximation is that $t_y - t_l$ be small compared to the period of the business cycle in X_t. In economic terms, it assumes that the length of the jobless recovery is a fraction of the length of the business cycle (for example, the duration peak-to-peak). Mathematically, the Taylor series expansion of employment growth with the Lagrange form of the remainder is:

$$\dot{l}\left(t_y\right) = \left(t_y - t_l\right)\ddot{l}\left(t_l\right) + \frac{1}{2}\left(t_y - t_l\right)^2 \ddot{l}\left(t_0\right), \quad t_0 \in \left(t_y, t_l\right).$$

If $t_y - t_l$ is small, i.e. if $\ddot{l}\left(t_0\right)$ is changes little in the interval $\left(t_y, t_l\right)$ compared to its variations over the business cycle, then $\ddot{l}\left(t_0\right)$ is close to $\ddot{l}\left(t_l\right)$ and the first-order approximation is valid. Figure A.1 contains a graphical version of this interpretation.

A.4 More details on the model and the data

The model predicts that the decline in the labor share of income is entirely due to routine occupations. Figure A.2 shows the labor share of income for routine and nonroutine occupations and supports this prediction.

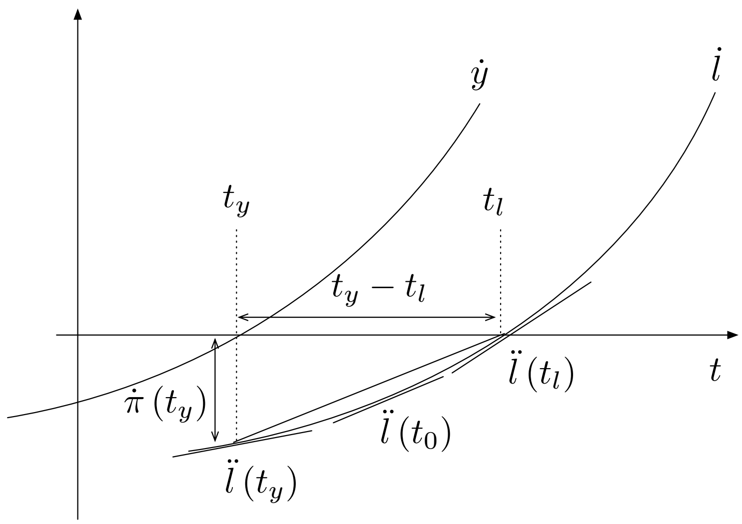

Figure A.1: The first-order approximation of the length of jobless recoveries is valid if jobless recoveries are short compared to the length of the business cycle.

Figure A.3 shows the path of the labor share in the data and in the model fitting US data. In the data, the labor share decreased 7.5% between the trough of the 1981 recession and the trough of the 2007 recession. The magnitude is similar in the model.

Figure A.4 shows the path of routine jobs in the model and in the data. The model has a good fit after 2000.

Figure A.5 shows the acceleration of the share of computers in fixed investment in the data and in the model. In the data, this share increased 8 percentage points between 1960 and 1980 and 21 percentage points from 1980 to 2000.

This paper explains the acceleration of routinization during recessions and jobless recoveries with computers. Yet, it predicts that computer investment is procyclical instead of accelerating in recessions. The absence of adjustment costs to capital leaves computer investment free to adjust: it falls in recessions and increases in recoveries. Figure A.6 shows the behavior of computer investment in the data and in the model. The model matches the behavior of computer investment: after a recession, computer investment simply catches up with its trend, rather than accelerating or increasing to a permanently higher level.

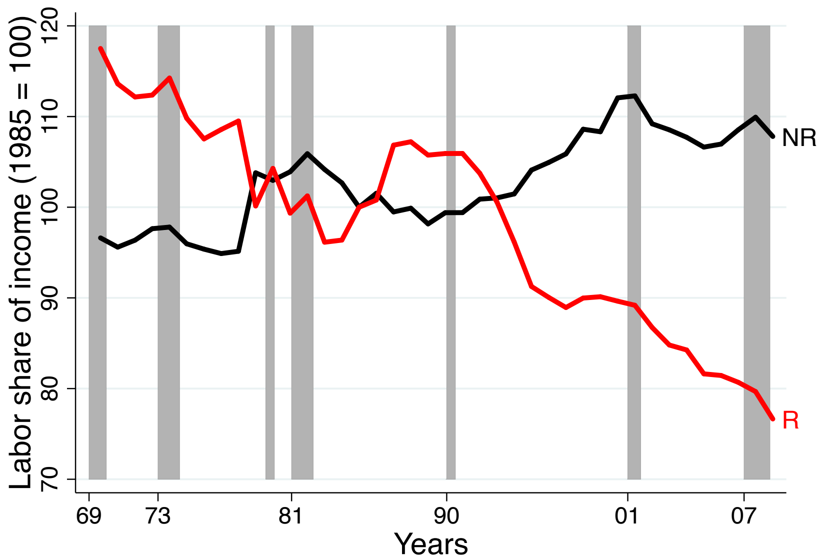

Figure A.2: The decline in the labor share of income is entirely due to routine occupations. Source: Current Population Survey, Occupational Information Network, and Federal Reserve Economic Database. Routine occupations are quartiles 3 and 4, nonroutine occupations are quartiles 1 and 2. The labor share of income for routine occupations is the labor income of routine occupations as a share of total labor income (held constant across the threshold years of 1982, 1992, and 2002), multiplied by the labor share of the nonfarm business sector (series PRS85006173).

A final prediction is that the investment share of output is procyclical and decreases in recessions, for two reasons. First, the absence of adjustment costs to capital implies that it is free to adjust to the recession. Second, the household has an incentive to smooth consumption but no incentive to smooth investment, so the burden of adjustment to a recession falls on investment. The calibration of the model also matches the cyclicality of the investment share of output, as shown in Figure A.7.

A.5 Extension of the model with nominal rigidities

This section extends the model with nominal rigidities and shows that the mechanism of nonroutine hoarding is robust to the possibility of rigid wages, unlike Jaimovich and Siu (2012).

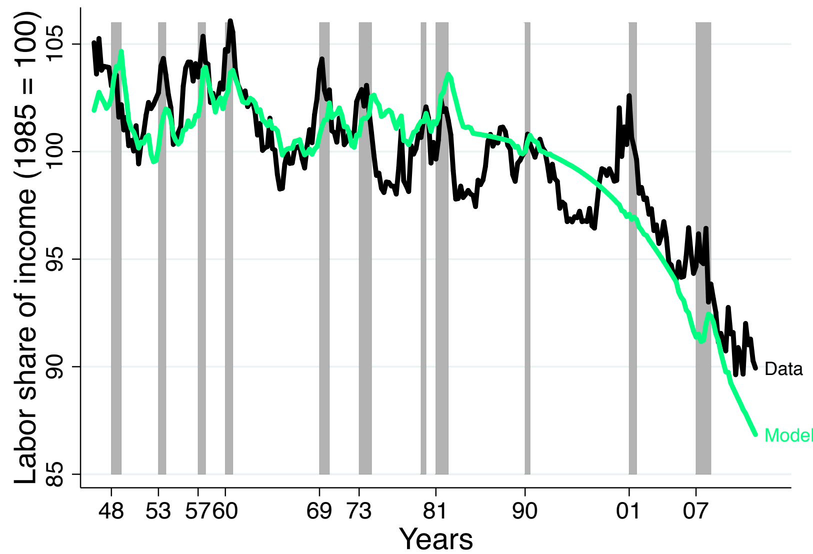

Figure A.3: The model matches the path of the labor share of income in the data.
Source: Federal Reserve Economic Database, with labor share of the nonfarm business sector. Shaded areas are NBER recessions.

The model is the same as the baseline model, with a change on the utility function for the household and the labor market clearing. The household has a labor supply curve fixed at L^S. The household has intertemporal utility

$$\sum_{t=0}^{\infty} \beta^t \log C_t.$$

Labor demand is bounded above by labor supply:

$$L_{NR,t} + L_{R,t} \leq L^S.$$

The wage is downward rigid:

$$w_{t+1} \geq w_t.$$

The first-order condition on labor supply for the household (equation $X_t L_t^{\frac{1}{\varepsilon}} = w_t$) is replaced by one complementarity slackness condition, where both of these inequalities hold

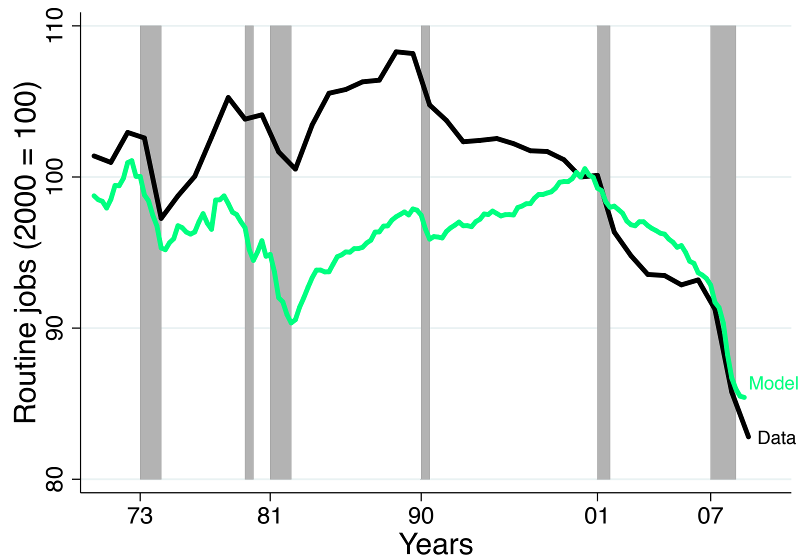

Figure A.4: The model matches the decline in employment of routine occupations in the data since 2000.
Source: Current Population Survey, Occupational Information Network, and model simulations. See text for details. Shaded areas are NBER recessions.

and one of them holds with equality:

$$\left(L^S - L_{NR,t} - L_{R,t}\right)\left(w_{t+1} - w_t\right) = 0.$$

The calibration of the model based on the path of US output follows the same procedure as the main text. Figure A.8 shows the result for the path of employment. Even with nominal rigidities, the hiring cost gives an incentive for the firm to hoard nonroutine jobs during the recession and to shift the burden of adjustment onto routine jobs. Recent recessions accelerate the structural decline of routine jobs.

A.6 More evidence on categories of employment

Acemoglu and Autor (2011) observe that the four categories of employment, defined by

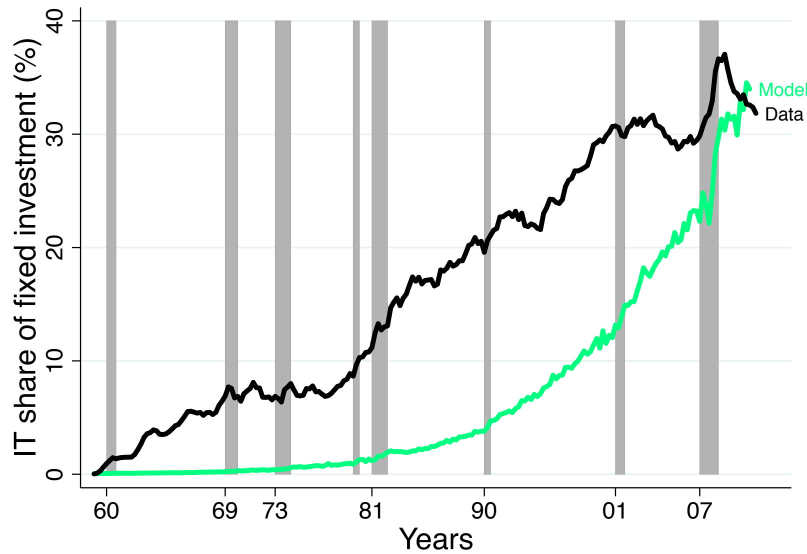

Figure A.5: The model and the data have an acceleration of the share of computers in fixed investment in recent decades.
Data: investment in computers, peripheral equipment, and software, divided by nonresidential fixed investment in equipment (BEA series B935RC0, B985RC0, and B010RC0, from Table 5.5.5U, "Private Fixed Investment in Equipment and Software by Type"). The series in the model and in the data are in nominal terms.

routine/nonroutine and manual/cognitive tasks, correspond broadly to the following occupation categories: "professional, managerial and technical occupations are specialized in nonroutine cognitive tasks (NR C); clerical and sales occupations are specialized in routine cognitive tasks (R C); production and operative occupations are specialized in routine manual tasks (R M); and service occupations are specialized in non- routine manual tasks (NR M)."

This categorization is sometimes coarse: accountants and auditors are classified as nonroutine cognitive according to Acemoglu and Autor but they are in Quartile 1 according to the measure of routinization in this paper. Nevertheless, the patterns of employment using the Acemoglu-Autor classification are similar to those with the routinization index: employment in routine occupations has a long-term decrease that accelerates during recessions; employment in nonroutine occupations has a long-term increase and is hoarded

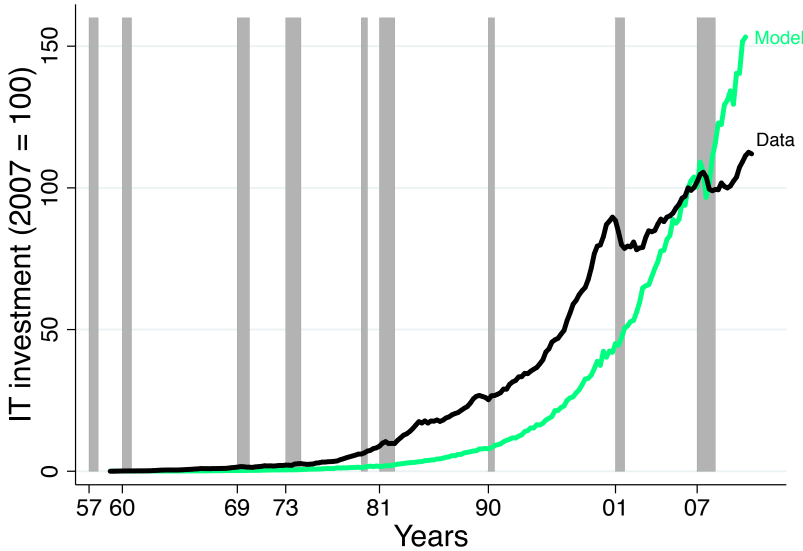

Figure A.6: After recessions, computer investment returns to trend, both in the data and in the model.
Source: see Figure A.5.

during recessions.

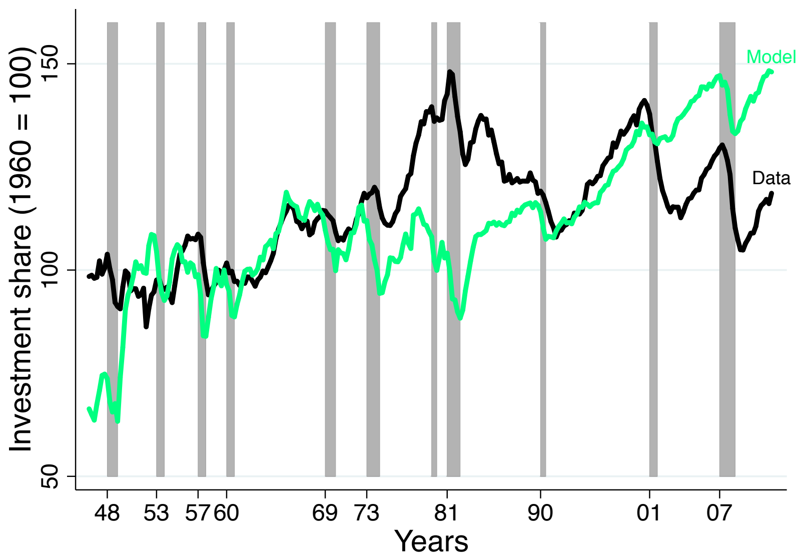

Figure A.7: The investment share of output is procyclical, both in the data and in the model.

Source: Federal Reserve Economic Database, Private Nonresidential Fixed Investment divided by Gross Domestic Product (both in nominal terms) and predictions of the model.

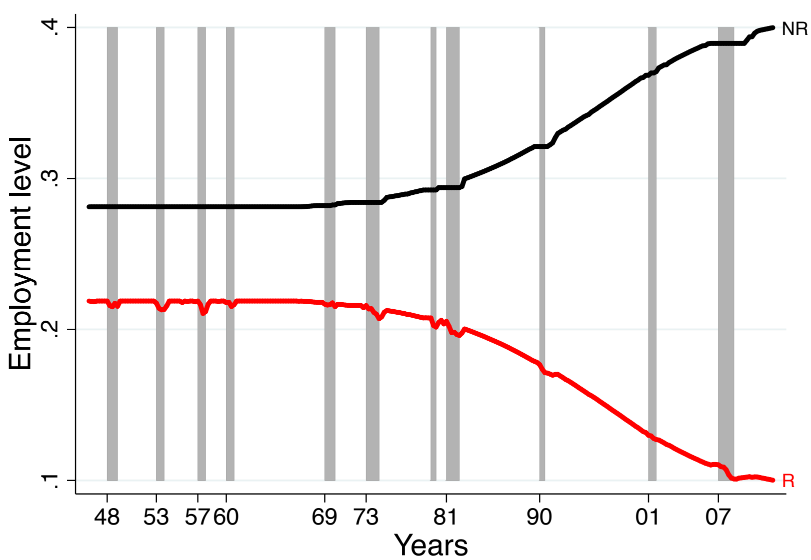

Figure A.8: The mechanism of nonroutine hoarding is robust to the possibility of wage rigidities.

See text for details.

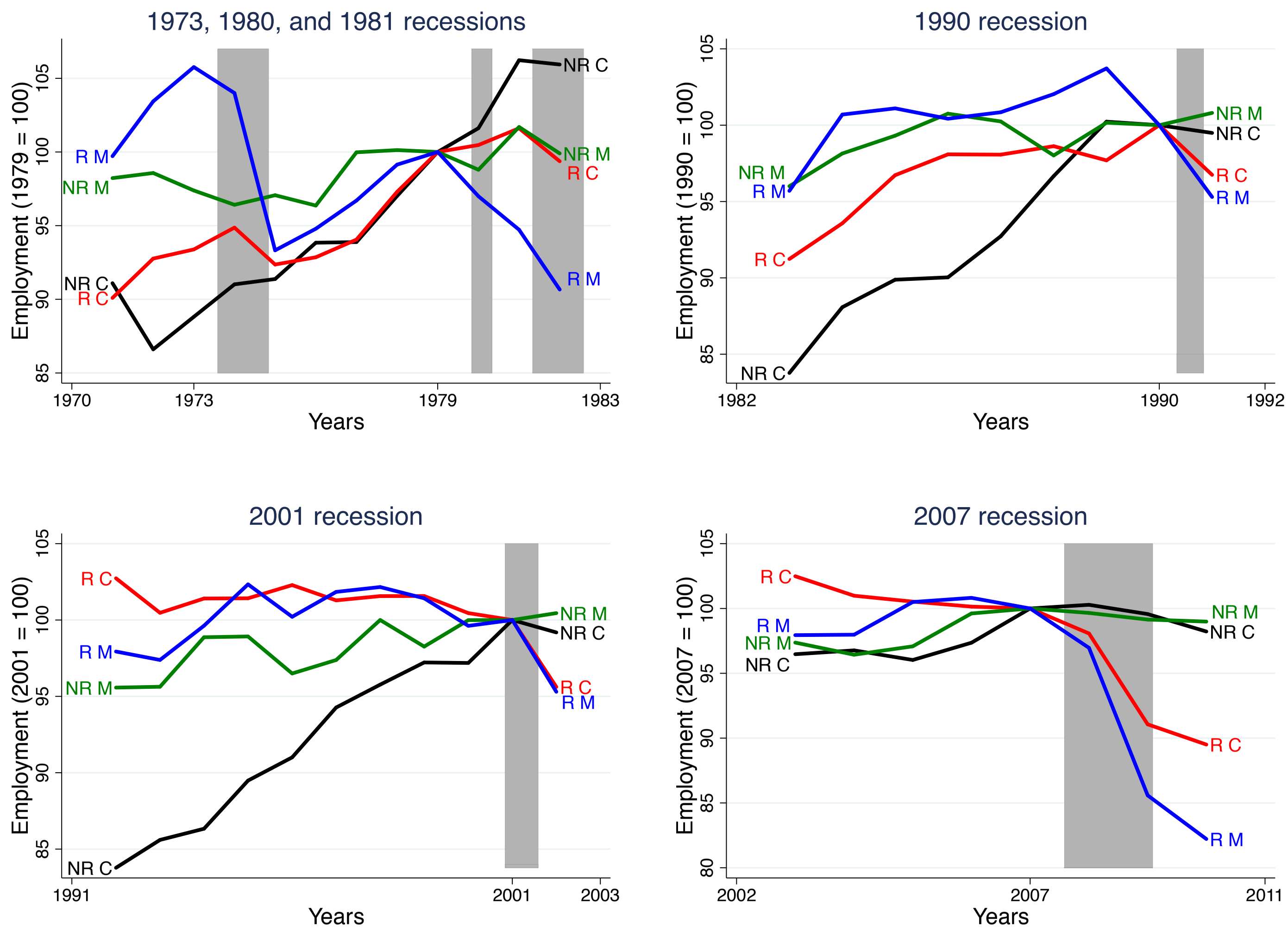

Figure A.9: The finding of routine job losses concentrated in recent recessions is robust to the classification of Acemoglu and Autor.

Source: Current Population Survey and Acemoglu and Autor (2011). Shaded areas are NBER recessions.

Appendix B

Appendix to Chapter 2

B.1 Census of Manufactures for the concrete industry

B.1.1 Matching across years

I matched plants between years 1929 and 1935 according to a similar procedure as Bresnahan and Raff (1991). Some plants sent two schedules to the Census Bureau; I aggregated them into a new plant by either averaging their responses if the two schedules cover the same period of operation, or by summing their results if they cover different periods. I considered that two plants were a match if:

1. one plant is from 1929 and the other from 1935
2. the two plants are located in the same state, county, and city
3. one of the following conditions hold:
   (a) two of the identifying fields coincide (name of plant, address, name of owner, street address, post office address),

(b) the plant in 1935 changed name, owner, or location, and conditions (a) hold between the change details in 1935 and the name, owner, or location in 1929,

4. no other plants match criteria (1-3).

As an example of condition 2, I considered small cities included in larger cities to be the same, such as Flushing and New York. I also considered nearby cities to be the same, such as Edina and Minneapolis, since concrete plants sometimes reported the location of the plant and sometimes the post office address of the general office. As an example of condition 3 (a), it is verified between a plant in 1935 with name "Gehirs" and address "23 Conklin St," and a plant in 1929 with owner "Gehirs" and address "Conklin street and Liberty Avenue." As an example of condition 3 (b), it is verified between a plant in 1935 with a name change from "Concrete pipe company" to "Concrete products, Inc." and a plant in 1929 with name "Concrete pipe company." As an example of condition 4, if two plants in Rockford, Illinois, share the name "Rockford plant" in 1929, then none is matched to the "Rockford plant" in 1935.

This procedure produces 742 plants merged between 1929 and 1935, of which 733 have information on the labor share of revenue in both years. Out of the 2,435 concrete plants operating in 1929, more than two thirds exited the market; out of the 1,108 concrete plants operating in 1935, a third entered the market.

The schedules changed slightly across plants. Some concrete plants in 1929 filled a schedule for the Census of Mines and Quarries, which omitted questions about electricity consumption and the quantity of output. Some plants filled other schedules and reported their output in different units, e.g. the number of laundry trays instead of their weight.

B.1.2 Data for the Census of Manufactures in other years

The schedules before 1929 and after 1935 were lost. The Census Bureau used them to compile information for the Statistical Abstracts and publications of the manufacturing industry. After such compilation, an Act of Congress gave the right to destroy the schedules. A 1971 letter by Dennis Rousey, Acting Chief of the Industrial and Social Branch, mentioned that "Since 1900, the schedules of agriculture censuses have been disposed of under Congressional authorization," with the manufacturing schedules possibly having a similar fate. An archivist told me that he was surprised that the schedules for 1929 to 1935 even survived, which he attributed to the relevance of the economic downturn. I searched for earlier or later schedules extensively and found only one surviving schedule from 1925, for the Crow Indian Mill in Colorado and kept at the National Archives in Denver, and one surviving schedule from 1939, for a German-owned company and the German American Bund that was seized during World War II. The schedules for the 1947 Census of Manufactures were transferred to non-safety microfilm, are disintegrating, and are "unavailable to researchers [because of] preservation issues and concerns."[1]

B.1.3 Categories of employment

The Census asked about two categories of employment, wage-earners and salaried workers, described in detail below. Wage-earners are present in all years and represent around 90% of employment. Officers of the corporation were sometimes reported on a special administrative schedule that is absent from the Census of Manufactures. In 1929, the Census included engineers and other technical employees as wage-earners. In 1935, technical employees had a separate category. This chapter considers all categories of employment, excluding proprietors, who had no salary, and salaried officers of the corporation, who were sometimes

[1] Electronic correspondence with the National Archives at College Park, Maryland.

reported on a different form. The details of employment categories suggest that the two types of employment are different from skilled/unskilled and from routine/nonroutine occupations.

- Categories of employment in 1929:
  - Proprietor or firm members
  - Principal officers of corporations
  - "Managers, superintendents, and other responsible administrative employees; foremen and overseers who devote all or the greater part of their time to supervisory duties; clerks, stenographers, bookkeepers, and other clerical employees on salary."
  - Wage-earners: "Skilled and unskilled workers of all classes, including engineers, firemen, watchmen, packers; also foremen and overseers in minor positions who perform work similar to that done by the employees under their supervision."
- Categories of employment in 1935:
  - Proprietor or firm members
  - Salaried officers of the corporation
  - Supervisory employees: "managers, superintendents, and other responsible administrative employees (including plant foremen whose duties are primarily supervisory but *not* including foremen and overseers in minor positions who perform work similar to that of the employees under their supervision"
  - Technical employees: "trained technicians, such as chemists, electrical and mechanical engineers, designers, who hold responsible positions requiring technical training and whose supervisory duties, if any, are only incidental"

- Clerical employees: "clerks, stenographers, bookkeepers, timekeepers, and other clerical employees (including laboratory assistants, draftsmen), whether in the office or in the factory"
- Wage-earners: "all time and piece workers employed in the plant (including the power plant and the maintenance, shipping, warehousing, and other departments) covered by this report, not including employees reported above. Include here working foremen and gang and straw bosses, but nor foremen whose duties are primarily supervisory."

B.1.4 Measurement of plant-level variables and industry background

The histograms in Figure B.1 suggest that the labor share of income have bell-shaped frequency curves with accurate measurement. The Census Bureau checked thoroughly these variables and mailed the plant for more information when it found outliers. In contrast, Figure B.2 suggests that the average price of electricity has considerable variation, up to 1 dollar per kilowatt-hour, at a time when the average price for the United States was 2.6 cents per kilowatt-hour.

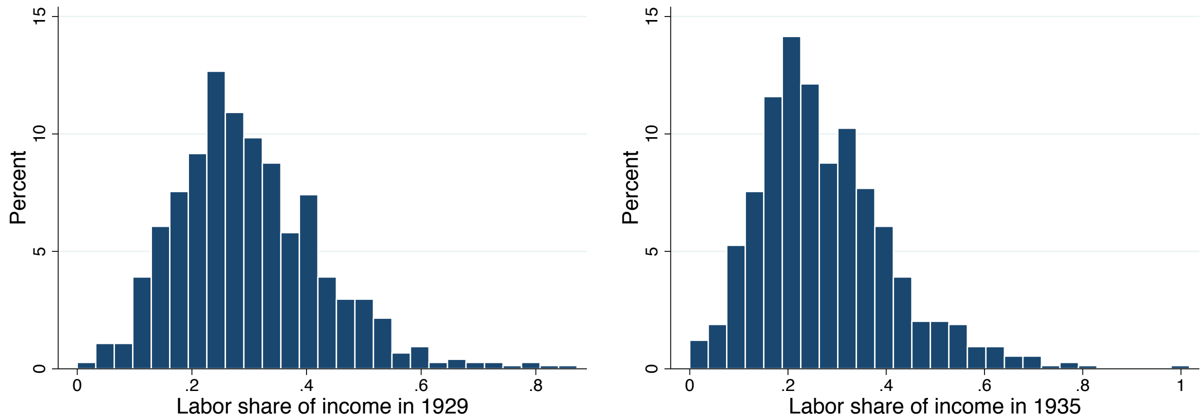

Figure B.1: The labor share of revenue of concrete plants in 1929 and 1935 has a bell-shaped distribution.

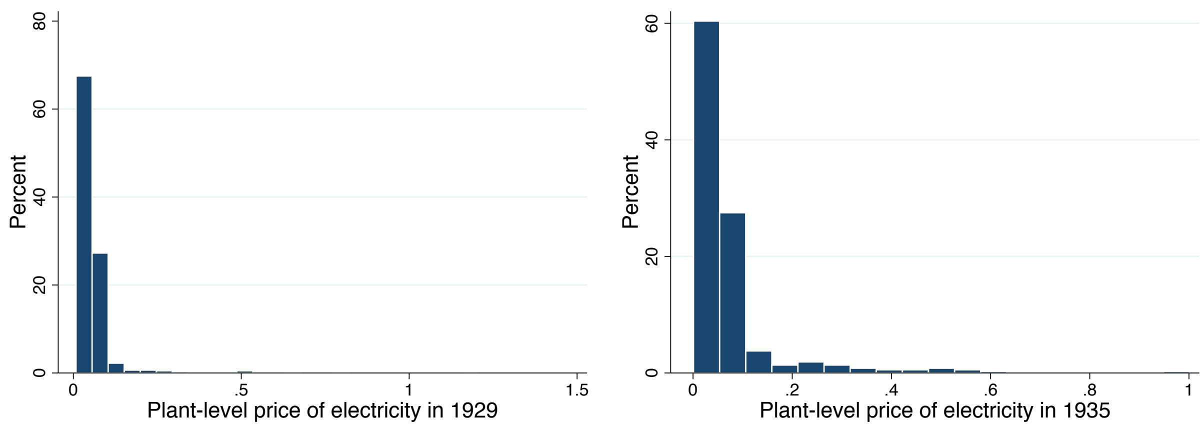

Figure B.2: The average price of electricity of concrete plants in 1929 and 1935 has a fat-tailed distribution.

This chapter considers the income $p_{i,t}Y_{i,t}$ to be revenue instead of value added. Revenue is a more robust measure and contains fewer outliers: for example, some plants during the Depression were operating at a loss and had negative value added (see Berman, Bound and Griliches (1994, page 383) for a similar approach).

Around half of concrete plants omitted kilowatts in 1935 but they did report the number and horsepower of electric motors. I imputed that quantity using a linear regression of kilowatts on number and horsepower, all in logarithms, and using the linear prediction for the missing quantities. I did a similar procedure for the 29 plants that omitted kilowatts in 1929.

Tennessee Valley Authority (1947) details the production of concrete for the Tennessee Valley Authority projects. It consists of mixing cement (often portland cement) with water and an aggregate (crushed stone, sand, or gravel). Production of concrete starts with collecting the aggregate, for example the sand of a river or the stone from a quarry. Plants convey the aggregate to their location and may need to crush the stone to obtain a finer aggregate. Plants mix the ingredients—cement, the aggregate, and water—to obtain a fluid substance that they pour onto a mold. The substance hardens with time. Plants sometime vibrate the mold to achieve more compactness between the aggregate and cement. They cure the concrete product with water, as cement requires a moist environment to harden further and increase strength. Plants may also polish the concrete product with sandblasting—a jet of water mixed with sand under high pressure to remove superficial irregularities. If plants convey the concrete product over a long distance to the delivery location, the product bears the risk of un-mixing.

B.2 Electricity data and background

B.2.1 Other measures of the price of electricity

Other measures of the price of electricity exist during this period but they are inferior to the state-level price of electricity used in the baseline regressions. First, the price of electricity paid by ice plants (Ziebarth, 2011) covers cities that coincide with only 200 concrete plants. Second, the city-level price of electricity for residential consumers for a typical bill of 25, 100, or 250 kilowatt-hours (Federal Power Commission, 1937) is a survey with measurement error due to retrospective questions asked in 1936, concerns residential consumers instead of industrial consumers, and has a significantly lower amount than the average demand by concrete plants in 1929 (1400 kilowatt-hours per month for concrete plants versus 250 kilowatt-hours for residential consumers). Third, the price of electricity by municipal utilities from the Census of Electric Light and Power Stations in 1927 and 1937 concerns a small market (5% of total kilowatt-hours).[2] Fourth, the Census of Electric Light and Power Stations published the price of electricity from both public and private utilities to industrial consumers, split by "small" (retail) and "large" (wholesale), but the "wholesale" numbers exist only half of the states to prevent disclosure of establishment information. To the best of my knowledge, there are no other measures for the price of electricity that are disaggregated geographically over this period.

Figure B.3 shows a scatter plot of the change in the state-level price of electricity and a Paasche index of the change in the price of electricity at the plant-level aggregated at the state-level: the two measures should be positively related but are negatively related.

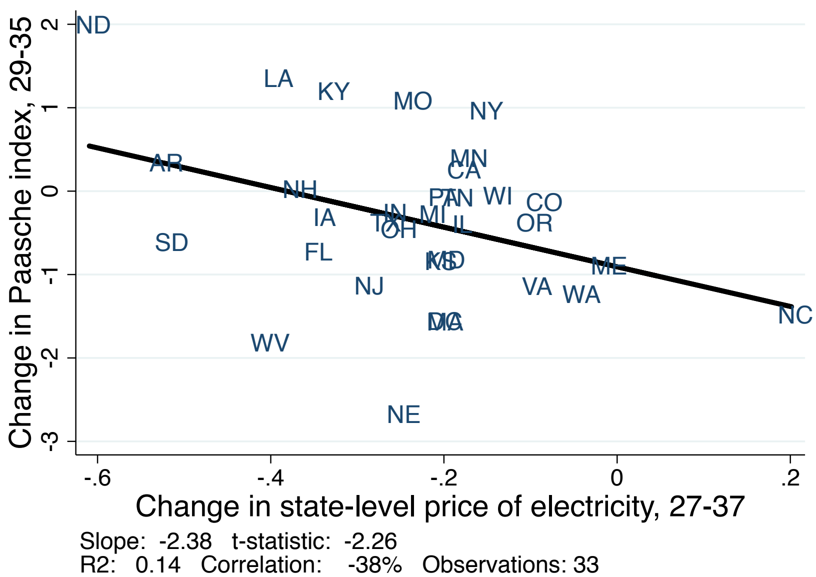

Figure B.3: The change in the Paasche index of the price of electricity is negatively related to the change in the state-level price of electricity.

[2]Census of Electric Light and Power Stations, 1927, page 71.

B.2.2 Pricing of electricity

Electric utilities offered several rate schedules. The Federal Power Commission published a glossary of terms and a summary of these rate schedules in 1936. All rates have a component of capacity, in kilowatts or horsepower, and of energy, in kilowatt-hours or Joules.

An electric bill consists of three types of charges: a customer charge, a demand charge, and an energy charge. The Federal Power Commission defines "customer charge" or "service charge" as "a component part of a rate schedule providing that a customer must pay a certain definite sum in a specified period (usually 1 month) without regard to the consumption of energy or the demand, for which he can use no energy or demand." It defines a "demand charge" as "a component part of a rate schedule which provides for a charge based upon the customer's demand or equivalent, without regard to the consumption of energy." It defines "energy charge" as "a component part of a rate schedule that provides for a charge based upon the amount of energy consumed." In short, the customer pays the demand charge for the right to use a given capacity from the grid, and it pays an energy charge for consumption of electricity.

Most rate schedules also define "maximum demand," which is often the aggregate capacity of electric appliances commonly used. For example, a plant may have a primary motor and a stand-by motor, each with a capacity of 100 kW. The plant may normally use only the primary motor and contracts for a maximum demand of 100 kW. If the plant happens to use both motors at the same time, it will have to pay a higher price for using more capacity than the maximum demand.

The *flat rate* schedule "provides for a specified charge per unit of time, irrespective of the amount of electric energy taken. For example: $2 per month per customer up to and including 6-50 watt lamps."

The *straight line meter rate* schedule "provides for a constant charge per unit of energy regardless of the amount consumed. For example: 5 cents per kilowatt-hour."

The *flat demand rate* schedule "bases the billing either on the demand or on some fixed characteristic indicative of demand but provides no charge for energy. For example: $50.00 per year per horsepower of demand."

The *flat and meter rate* schedule is a two-part tariff with "two components, the first of which is a customer (or service) charge and the second of which is a price for the energy consumed."

The *block meter rate* schedule "divides the total amount of energy to be consumed during a definite period into prescribed blocks and provides a different rate for each."

The *Hopkinson demand rate* schedule has "two components, the first of which is a charge for demand, and the second a charge for the energy consumed."

The *block Hopkinson demand rate* schedule has "either the demand charge or the energy charge or both are arranged in blocks. For example, a demand charge of $1.25 for the first 50 kilowatts of maximum demand per month, and $1.00 per kilowatt for all above 50 kilowatts of maximum demand per month. Plus: an energy charge of 3 cents per kilowatt-hour for the first 1,000 kilowatt-hours used per month, and 1 cent per kilowatt-hour for all energy used in excess of 1,000 kilowatt-hours per month."

The *step meter rate* schedule has "a charge per unit of energy [that] is constant for all kilowatt-hours consumed during the billing period, the charge per unit depending upon the total consumption. For example: if 1 to 25 kilowatt-hours are used in a month, 5 cents per kilowatt-hour; if 26 to 50 kilowatt-hours are used in a month, 3 cents per kilowatt-hour (for all the energy including the first 25 kilowatt-hours)."

The *three-part rate* schedule "provides three components for determining the total bill: customer charge, demand charge, and energy charge. For example: 50 cents per month per meter. Plus: a demand charge of $1.25 per month per kilowatt for the first 25 kilowatts of maximum demand in the month; 90 cents per month per kilowatt for the excess of the maximum demand over 25 kilowatts. Plus: an energy charge of 1.5 cents per kilowatt-hour."

Furthermore, rate schedules may have clauses providing for additional charges in the event of large increases in the price of coal, the price of commodities, or wages.

B.2.3 Technical progress in the generation of electricity

Figure B.4 illustrates the exponential decrease in the price of electricity over the first half of the 20th century. Gordon (1992, Table 1) estimates the rate of decrease in the price of electricity at 7% per year between 1899 and 1948. The price of electricity increased during the Great Depression because of deflation in the consumer price index. In a more general model with irreversible investment, firms would have difficulty adjusting their capital stock to cyclical changes in the price of electricity and would react to the trend in the price of electricity rather than to the fluctuations. Furthermore, the nominal price of electricity decreased by 21 log-points in the sample of concrete plants (see Table 2.1).

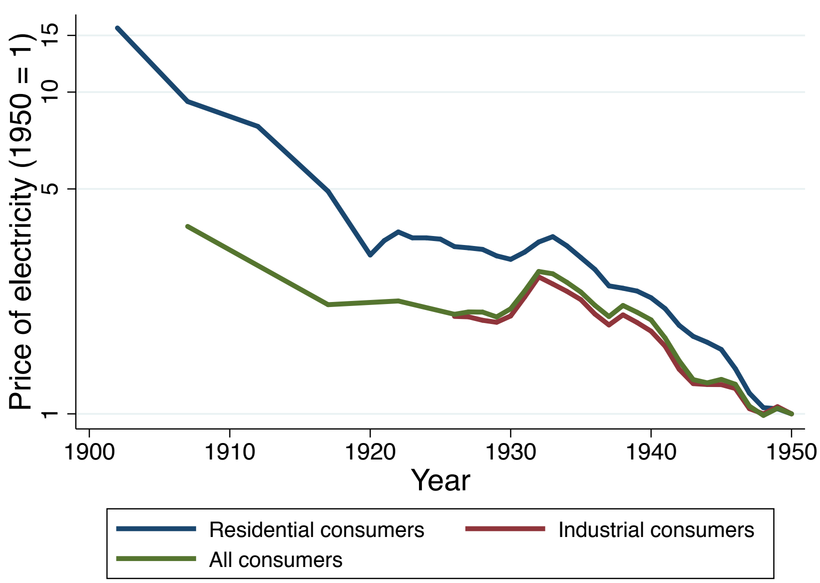

Figure B.4: The real price of electricity decreased exponentially in the first half of the 20th century.

The price of electricity is in cents per kilowatt-hour from the Historical Statistics of the United States, series Db234, Db235, and Db237. The price deflator is the consumer price index from the BLS, series Cc1. The rate of decrease of the price of electricity for residential consumers is 5.8%.

The technology to produce electricity from coal improved over the first half of the 20th century. The most common fuel was bituminous coal: "representing 77.1 percent of the total consumed, while natural gas is second in importance, reporting 12.4 percent of the total" (Census of Electric Light and Power Stations, 1937, page 5).

The technical progress benefitted the coal technology but not the hydroelectric technology:

> In generating electricity from coal even the largest and most modern electric power stations are able to utilize only about 25 per cent of the heat units available in the coal. ... On the other hand, modern hydro-electric machinery now transforms into electricity more than 90 per cent of the energy in falling waters, leaving little opportunity for radical improvements in present-day hydro-electric practice. (The electric light and power industry, 1931, page 43)

Hughes (1993) also describes the economies of scale of electrification in Western Society over the period 1880-1930.

B.3 Proofs

Proof of equations (2.3.2) and (2.3.3). This proof omits index i. The firm maximizes intertemporal profits

$$\sum_{t=0}^{\infty} D_{0,t} \left(A_{i,t} K_{NE,i,t}^{\alpha} L_{NR,t}^{\beta} \left(K_{E,i,t}^{\rho} + L_{R,i,t}^{\rho} \right)^{\frac{\gamma}{\rho}} - w_t \left(L_{NR,t} + L_{R,t} \right) - r_{NE,t} K_{NE,t} - r_{E,t} K_{E,t} \right),$$

where $\rho = (\sigma - 1)/\sigma$. The firm has no accumulation constraints on capital or labor and the intertemporal maximization problem collapses to a sequence of static maximization problems. The first-order conditions for profit-maximization, taking prices as given, are:

$$\begin{aligned}
MPK_{NE,t} &= \frac{\alpha Y_t}{K_{NE,t}} = r_{NE,t}, \\
MPL_{NR,t} &= \frac{\beta Y_t}{L_{NR,t}} = w_t, \\
MPK_{E,t} &= \gamma Y_t L_{R,t}^{\rho-1} \left(K_{EI,t}^{\rho} + L_{R,t}^{\rho}\right)^{-1} = r_{E,t}, \\
MPL_{R,t} &= \gamma Y_t L_{R,t}^{\rho-1} \left(K_{E,t}^{\rho} + L_{R,t}^{\rho}\right)^{-1} = w_t,
\end{aligned}$$

where MPF is the marginal product of factor F. The ratio of electric capital to employment in routine occupations is:

$$\frac{K_{E,t}}{L_{R,t}} = \left(\frac{r_{E,t}}{w_t}\right)^{-\sigma}.$$

The labor share of income is:

$$\begin{aligned}
\frac{w_t L_t}{Y_t} &= \frac{w_t L_{NR,t}}{Y_t} + \frac{w_t L_{R,t}}{Y_t}, \\
&= \beta + \gamma L_{R,t}^{\rho} \left(K_{E,t}^{\rho} + L_{R,t}^{\rho}\right)^{-1}, \\
&= \beta + \gamma \left(1 + \left(\frac{K_{E,t}}{L_{R,t}}\right)^{\rho}\right)^{-1}, \\
&= \beta + \gamma \left(1 + \left(\frac{r_{E,t}}{w_t}\right)^{-\rho\sigma}\right)^{-1}, \\
&= \beta + \gamma \left(1 + \left(\frac{r_{E,t}}{w_t}\right)^{1-\sigma}\right)^{-1}.
\end{aligned}$$

The routine share of labor is:

$$\begin{aligned}
\frac{L_{R,t}}{L_t} &= \frac{L_{R,t}}{L_{NR,t} + L_{R,t}}, \\
&= \left(1 + \frac{L_{NR,t}}{L_{R,t}}\right)^{-1}, \\
&= \left(1 + \frac{\beta}{\gamma}\frac{r_{E,t}^{1-\sigma} + w_t^{1-\sigma}}{w_t^{1-\sigma}}\right)^{-1}.
\end{aligned}$$

The electric capital-total labor ratio is :

$$\begin{aligned}
\frac{K_{E,t}}{L_t} &= \frac{K_{E,t}}{L_{R,t}}\frac{L_{R,t}}{L_t}, \\
&= \left(\frac{r_{E,t}}{w_t}\right)^{-\sigma}\left(1 + \frac{\beta}{\gamma} + \frac{\beta}{\gamma}\left(\frac{r_{E,t}}{w_t}\right)^{1-\sigma}\right)^{-1}, \\
&= \left(\frac{r_{E,t}}{w_t}\right)^{-1}\left(\frac{\beta}{\gamma} + \left(1 + \frac{\beta}{\gamma}\right)\left(\frac{r_{E,t}}{w_t}\right)^{\sigma-1}\right)^{-1}.
\end{aligned}$$

B.4 Additional regressions

Table B.1 shows the baseline regressions including the change in the state-level price of cement as a proxy for the price of intermediate inputs. The price of cement was digitized by Ziebarth (2011), who kindly provided me with an electronic version of the dataset. The price of cement is irrelevant for the change in the labor share of income and the electricity coefficient is stable around 1 in OLS and 2 in IV, although it loses statistical significance in Instrumental Variables. The coefficient is statistically significant in reduced form. If intermediate inputs enter the production function in Cobb-Douglas form, the theory predicts that their price is summarized by the price of output $p_{i,t}$. The price of intermediate inputs should be absent from the expression for the labor share of income in the same way that the rental rate of non-electric capital was absent from the expression for the labor share of income in equation (2.3.2).

Dependent variable: $\Delta \log(w_{i,t}L_{i,t}/p_{i,t}Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log(p_{E,k,t}/w_{k,t})$	0.780**	2.491*	
(state-level)	(0.333)	(1.467)	
$\Delta \log p_{cement,k,t}$	-0.0195	0.188	0.0063
(state-level)	(0.217)	(0.328)	(0.184)
$coal_{k,1927}$			-0.174**
(state-level)			(0.0681)
Constant	-0.186***	-0.371**	0.0196
	(0.0353)	(0.154)	(0.0571)
Observations	680	680	680
R-squared	0.01		0.01
First-stage F-statistic		6.245	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.1: The baseline results are robust to including the price of cement.

Table B.2 presents the results for labor productivity (with quantities). The coefficients have the expected sign: the decrease in the price of electricity caused an increase in labor productivity, consistent with the prediction of the model. The standard error of this coefficient is large because output quantities are measured with error.

Dependent variable: $\Delta \log (Y_{i,t}/L_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log (p_{E,k,t}/w_{k,t})$	-0.365	-2.523*	
(state-level)	(0.574)	(1.451)	
$coal_{k,1927}$			0.204
(state-level)			(0.128)
Constant	-0.218***	0.0106	-0.401***
	(0.0776)	(0.175)	(0.0920)
Observations	503	503	503
R-squared	0.001		0.005
First-stage F-statistic		14.83	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.2: The effect of the price of electricity on labor productivity conforms to the theoretical prediction.

Tables 2.6 shows a falsification test with the fuel share of revenue, similar to the falsification test with the materials share of income in Table 2.6. Table B.3 suggests that initial coal dependence has an effect on the change in the fuel share of revenue that is significant at the 10% level. It is possible that states that were initially more dependent on coal power may also have better access to bituminous coal, the main fuel used by the concrete industry. Table B.4 shows that the baseline results for electricity are unchanged when including the change in the fuel share of revenue as a control variable, allaying the concerns about the importance of the fuel share as a competing channel for the effect of electricity on the labor share of income.

Dependent variable: $\Delta \left(Fuel_{i,t}/p_{i,t}Y_{i,t} \right)$

Method:	OLS	IV	reduced-form
$\Delta \log \left(p_{E,k,t} \right)$	0.0051	-0.0187	
(state-level)	(0.00537)	(0.0160)	
$coal_{k,1927}$			0.00162*
(state-level)			(0.000917)
Constant	-7.83E-05	0.0025	-0.000649
	(0.000831)	(0.00203)	(0.000533)
Observations	742	742	742
R-squared	0.001		0.001
First-stage F-statistic		14.89	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.3: Falsification test: the decrease in the price of electricity has no effect on the fuel share of revenue.

As the fuel share of revenue is small, around 1%, this regression uses the percentage point change instead of the log-change.

Dependent variable: $\Delta \log(w_{i,t}L_{i,t}/p_{i,t}Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log(p_{E,k,t}/w_{k,t})$	0.689**	2.164**	
(state-level)	(0.281)	(0.854)	
$\Delta FUEL_{i,t}/p_{i,t}Y_{i,t}$	3.093	2.959	3.449
(plant-level)	(2.018)	(2.048)	(2.079)
$coal_{k,1927}$			-0.188***
(state-level)			(0.0587)
Constant	-0.185***	-0.345***	0.0193
	(0.0325)	(0.0939)	(0.0438)
Observations	733	733	733
R-squared	0.012		0.016
First-stage F-statistic		7.405	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.4: The baseline results are robust to including the change in the fuel share of revenue as a control variable.

Table B.5 shows the results of the baseline regressions using an alternative instrument: the hydroelectric potential estimated by Douglas et al. (2006, Table 7, page 26). The first-stage F-statistic is smaller than the coal share instrument. Nevertheless, the point estimates for the electricity regressor are similar. The results for electricity usage are similar to the results in the text, with lower statistical significance, and are omitted.

Dependent variable: $\Delta \log (w_{i,t} L_{i,t} / p_{i,t} Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log (p_{E,k,t} / w_{k,t})$	0.695**	1.196*	
(state-level)	(0.277)	(0.642)	
hydro potential$_k$			0.0397*
(state-level)			(0.0200)
Constant	-0.184***	-0.239***	-0.372***
	(0.0326)	(0.0695)	(0.126)
Observations	733	730	730
R-squared	0.008	0.005	0.009
First-stage F-statistic		6.486	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.5: The baseline results are robust to using hydroelectric potential as an alternative instrument.

Table B.6 shows the plant-level correlations between the plant-level change in the labor share of income and the plant-level change in the price of electricity, with several specifications. The coefficient on the plant-level price of electricity is stable around 0.07, statistically, and economically significant. A 1% decrease in the price of electricity is associated with a 0.07% decrease in the labor share of income. The regression coefficient has the same order of magnitude as the simulations of the model. The first two columns use only the plant-level price of electricity, with and without dummies for each state. The next two columns include the change in the plant-level wage. The coefficient on plant-level wages is positive, in contrast to the model's prediction of a negative. This specification may be problematic since the change in the plant-level wage could also be an outcome variable and may be correlated with the error term, leading to a biased estimate. The last column shows a regression using the change in the average wage at the state-level for all manufacturing plants between 1929 and 1935. This proxy for the wage in all of manufacturing is less likely to be an outcome variable of the price of electricity paid by concrete plants. The wage coefficient is then negative, economically significant, and statistically significant at the 10% level. These regressions contain endogeneity bias but they provide a source of variation that is orthogonal to the state-level variation in the baseline regressions.

Dependent variable: $\Delta \log (w_{i,t} L_{i,t} / p_{i,t} Y_{i,t})$

$\Delta \log p_{E,i,t}$	0.0608**	0.0813**	0.0598**	0.0741**	0.0638**
(plant-level)	(0.0300)	(0.0318)	(0.0281)	(0.0300)	(0.0300)
$\Delta \log w_{i,t}$			0.465***	0.431***	
(plant-level)			(0.0662)	(0.0702)	
$\Delta \log w_{k,t}$					-1.353*
(state-level)					(0.781)
Constant	-0.0345	0.111	0.161***	0.269	-0.367*
	(0.0298)	(0.539)	(0.0394)	(0.510)	(0.194)
State dummies	No	Yes	No	Yes	No
Observations	337	337	337	337	337
R-squared	0.012	0.131	0.139	0.229	0.021

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.6: The decrease in the price of electricity at the plant-level is correlated with a decrease in the labor share of revenue.

Table B.7 shows that the coefficients are stable when using the labor share of value added instead of income (value added is income minus the cost of materials, fuel, and electricity).

Dependent variable: $\Delta \log \left(w_{i,t} L_{i,t} / ValueAdded_{i,t}\right)$

Method:	OLS	IV	reduced-form
$\Delta \log \left(p_{E,k,t} / w_{k,t}\right)$	0.647**	1.919**	
(state-level)	(0.288)	(0.799)	
$coal_{k,1927}$			-0.166***
(state-level)			(0.0612)
Constant	-0.155***	-0.293***	0.0291
	(0.0351)	(0.0932)	(0.0451)
Observations	732	732	732
R-squared	0.006		0.007
First-stage F-statistic		14.89	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.7: The baseline results are robust to using the labor share of value added instead of revenue.

Tables B.8 and B.9 show the baseline regressions using state-level controls of GDP in 1929 and the share of population working in agriculture in 1920. The electricity coefficient is also stable between 1 and 2.

Dependent variable: $\Delta \log (w_{i,t} L_{i,t} / p_{i,t} Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log p_{E,k,t}$	1.087***	1.678***	
(state-level)	(0.266)	(0.517)	
share of farm in 1920	0.424***	0.554***	0.133
(state-level)	(0.148)	(0.170)	(0.159)
$coal_{k,1927}$			-0.172***
(state-level)			(0.0606)
Constant	-0.326***	-0.421***	-0.0205
	(0.0565)	(0.0852)	(0.0668)
Observations	733	733	733
R-squared	0.019	0.014	0.012
First-stage F-statistic		12.87	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.8: The baseline regressions are robust to controlling for the state-level share of population in farms.

Dependent variable: $\Delta \log (w_{i,t} L_{i,t} / p_{i,t} Y_{i,t})$

Method:	OLS	IV	reduced-form
$\Delta \log p_{E,k,t}$	1.133***	1.695***	
(state-level)	(0.289)	(0.601)	
log-GDP in 1929	-0.0676**	-0.0894***	-0.016
(state-level)	(0.0256)	(0.0318)	(0.0275)
$coal_{k,1927}$			-0.175***
(state-level)			(0.0627)
Constant	0.314	0.429**	0.142
	(0.191)	(0.217)	(0.216)
Observations	733	733	733
R-squared	0.018	0.014	0.011
First-stage F-statistic		12.46	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.9: The baseline regressions are robust to controlling for the state-level initial income.

Table B.10 suggests that the regressions are robust to controlling for a predictor of the business cycle, such as the county-level growth rate of housing construction from 1920-1924 to 1925-1929 from the 1940 Census of Housing. The Census Bureau asked non-farm dwellers about the year of construction of their dwelling and aggregated residential construction by county and quinquennium. This information was digitized by Kimbrough and Snowden (2007), who kindly provided me with an electronic version of the dataset.

Dependent variable: $\Delta \log \left(w_{i,t} L_{i,t} / p_{i,t} Y_{i,t}\right)$

Method:	OLS	IV	reduced-form
$\Delta \log \left(p_{E,k,t} / w_{k,t}\right)$	0.890***	1.847***	
(state-level)	(0.254)	(0.596)	
$\log \left(H_{25-29} / H_{20-24}\right)$	-0.127**	-0.191***	-0.0443
(county-level)	(0.0530)	(0.0725)	(0.0550)
$coal_{k,1927}$			-0.176***
(state-level)			(0.0633)
Constant	-0.187***	-0.282***	0.0193
	(0.0298)	(0.0597)	(0.0441)
Observations	730	730	730
R-squared	0.014		0.011
First-stage F-statistic		18.06	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B.10: The baseline results are robust to controlling for the business cycle.
Details: see text. Because the measure of housing is at the county-level, this table reports the F-statistic from the first-stage of the IV regression, instead of a separate regression at the state-level as in the other tables of this chapter.