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Aggregate Evidence on Price Rigidities and the Inflation-Output Trade-Off: A Factor Analysis of Factor Shares

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We find inflation statistically significant in explaining movements in income shares of labor, capital and profits, controlling for other potential sources of these co-movements, such as competition or unionization. These controls are generated through factor analysis, which explains covariances of observed variables in terms of underlying unobservables. Accounting for the observed co-movement between inflation and the income shares without nominal rigidities is difficult, since income shares are not likely to impact inflation, or monetary policy, and are independent of most variables and shocks, including those to productivity. Hence, the relationship supports the relevance of nominal rigidities at the aggregate level.

Key Words: Price rigidities; Inflation-output trade-off; Phillips curve; Sticky prices; Monetary neutrality; Factor analysis.
JEL Classification Numbers: E40, E31, E25.

1. INTRODUCTION

The hypothesis that money affects the aggregate real economy in the short run, despite being neutral in the long run, is one of the most controversial in economics, mainly due to a lack of convincing empirical evidence of short-run non-neutrality and its relevance at the aggregate level. Nonetheless, great effort has gone into studying nominal rigidities through which money could affect the real economy, and using these frameworks, especially the sticky-price models proposed by Calvo (1983) and Rotemberg (1982), not only to analyze monetary policy, but also to guide it.[1] Much of the work was sparked by the well-known Phillips (1958) curve, which did not stand the test of time, but has still had an enormous im-

[1]Some prominent examples include Clardia, Gali and Gertler (1999) and Woodford (2003).

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pact on the field. In fact, later contributions have rationalized why the Phillips curve relationship can change over time, thus justifying the deterioration of the original empirical evidence. Consequently, many appear to have accepted that nominal rigidities are not easily discernible in aggregate data, and some have turned to look for these in disaggregate data (Lach and Tsiddon (1992), Kashyap (1995), Levy et al (1997), Bils and Klenow (2004), Klenow and Kryvstov (2008) and Gagnon (2009)). However, such studies cannot demonstrate the relevance of nominal rigidities at the aggregate level, since their effects can wash out, as illustrated by Caplin and Spubler (1987), or Golosov and Lucas (2007). The present paper studies how inflation can affect real aggregate variables through nominal rigidities that distort price-setting, in order to assess the aggregate relevance of such rigidities empirically. We find evidence consistent with nominal rigidities distorting price-setting in U.S. aggregate data in that inflation raises the income share of labor and lowers that of profits. We obtain similar results for Australia, Canada, Finland, France and the U.K., the countries for which at least thirty years of the necessary quarterly national income account data is available.

Many studies examine nominal rigidities empirically using aggregate data, most notably Fuhrer and Moore (1995), Roberts (1995), Rotemberg (1996), Fuhrer (1997), Gali and Gertler (1999), Sbordone (2002), Christiano, Eichenbaum and Evans (2005), Korenok and Swanson (2007) and Reis (2009). The main difficulty is that theory predicts that most aggregate variables should be correlated even without such rigidities. For example, Freeman and Huffman (1991) argue that a positive co-movement between inflation and output can be explained without nominal rigidities by both variables reacting to productivity shocks. The problem is aggravated by the fact that monetary policy responds to aggregates, especially output. For example, Wang and Wen (2005) argue that many of the features observed in U.S. inflation and output data that might look like evidence of nominal rigidities can be explained by a model without rigidities when policy follows the Taylor (1993) rule. Hence, we propose focusing on the factor shares of income instead of output. They are aggregate variables that should be more robust to changes in productivity, government spending, household preferences, and most other variables usually considered relevant for business cycles, but are affected by nominal rigidities through their distortions to price-setting. Furthermore, income shares are not usually considered to impact monetary policy, nor do they depend on variables thought to influence policymaking.

Many a hypothesis has been proposed describing nominal rigidities through which money could affect the real aggregate economy by distorting price-setting. The most prominent ones are menu costs (Rotemberg (1982), Calvo (1983), and Golosov and Lucas (2007)), negotiation costs (Fischer

(1977) and Taylor (1980)), monetary misperceptions (Lucas (1972), and Phelps and Taylor (1977)) and costly information-gathering (Mankiw and Reis (2002)). Our objective is not to model these in detail, but rather to provide a framework that encompasses all in terms of the aggregate impact of their distortions to price-setting. There are two distinct effects, one working through relative prices, the other via the average markup. By making price-adjustment idiosyncratic, nominal rigidities distort relative prices, reducing total factor productivity as a result of the cost-minimizing mix of intermediate goods differing from the productivity-maximizing mix, thus having a negative impact on output and welfare. At the same time, nominal rigidities affect the markups households pay, which can reduce or raise output and welfare due to dead-weight losses from imperfect competition, depending on whether they raise or lower the average markup paid. An inflation-output trade-off requires that the average markup paid fall with inflation, and that this effect dominate the one through relative prices and total factor productivity.[2]

As markups fall due to increased competition, the share of income that goes to profits falls, and the shares incurred by labor and capital increase. While inflation has no impact on the degree of competition in the absence of nominal rigidities, the causality could go in the opposite direction, since output increases with competition, which could affect the rate of inflation through money demand, or monetary policy. Hence, controlling for changes in competition is crucial when studying the relationship between the income shares and inflation.[3] However, doing so is difficult, since no direct measures are available, and the ones that are at hand are very noisy measures, affected by other variables, such as productivity. To get around this, we use factor analysis, developed by Spearman (1904) and Thurstone (1931) to describe the covariances among a group of observable variables in terms of the underlying unobservables. The method is common in psychology, where it originated, and in sociology and political science. It has also been studied and applied in economics, see for example Megee (1965), Scott (1966), Goldberger (1972), Quah and Sargent (1993), Forni and Reichlin (1996 and 1998), Stock and Watson (1998 and 1999) and Bernanke and Boivin (2003)). Factor analysis is usually used for data reduction, we

[2] Domowitz, Hubbard and Petersen (1986), Haskel, Martin and Small (1995) and Hall (2012) find that markups are procyclical in U.S. data, while Bils (1987), Galeotti and Schianterelli (1998), Rotemberg and Woodford (1999), and Gali, Gertler and Lopez-Salido (2007) find they are countercyclical.

[3] Using U.S. data, Gali and Gertler (1999) and Sbordone (2002) regress the rate of inflation on the income share of labor, using it as a measure of real marginal costs, and find a statistically significant positive relationship. Gali, Gertler and Lopez-Salido (2001) find the same for the Euro area. Testing a particular Phillips curve relation, their estimated equation includes expected next-period inflation, and sometimes also lags of inflation, but no controls for changes in the degree of competition.

use it instead to separate the effects of competition and inflation. We find that controlling for changes in competition reduces the estimated impact of inflation to about one-third of the uncontrolled estimate.

The novelty of our approach is threefold. First, we provide a framework to study the impact of nominal rigidities on the aggregate economy that is general enough to encompass the most prominent theories. This has the advantage of circumventing potential biases in estimation, and in the interpretation of results, that binding oneself to a particular theory can lead to. Second, focusing on income shares instead of output, or input use, to measure the impact of nominal rigidities, which we show should be more robust to spurious correlation generated by endogenous monetary policy, productivity shocks, or other variables. Third, using factor analysis to control for unobservable variables, in particular changes in competition, which can generate co-movements between inflation and markups, output and input use even in the absence of nominal rigidities.

Our dynamic general equilibrium model builds on that of Blanchard and Kiyotaki (1987). The next two sections present the producers and equilibrium conditions, respectively. The following three sections study the impact nominal rigidities have on total factor productivity, factor markets and factor shares of income, respectively. Finding that evidence of price rigidities should be easiest to identify in the income shares, the subsequent section presents the data for the U.S. nonfinancial corporate business sector, which comprises about half of U.S. GDP. Factor analysis is used in the subsequent section to isolate the effects of inflation through price rigidities, by controlling for changes in competition and other contingencies that affect the income shares. The ensuing section looks at the international data. We find that the income share of labor rises with inflation, while that of profits tends to fall.

2. PRODUCERS

In any period t, each of the continuum of measure one identical households produce y_t units of final good by combining a continuum of differentiated intermediate goods x_{it}, indexed by $i \in [0,1]$, according to the Dixit-Stiglitz (1977) production function

$$y_t = \gamma_t \left(\int_0^1 x_{it}^{\frac{\theta_t - 1}{\theta_t}} \, di \right)^{\frac{\theta_t}{\theta_t - 1}} \tag{1}$$

where $\theta_t \in (1, \infty)$ is the elasticity of substitution between any two intermediate goods, and $\gamma_t > 0$ is the productivity with which intermediate goods can be combined into final goods. Assuming intermediate goods are the only inputs required to produce final goods, each household chooses the optimal mix of these so as to minimize the cost of providing final goods $\int_0^1 P_{it} x_{it} di$ with respect to x_{it} for all $i \in [0,1]$, subject to the production function (1), where P_{it} is the price of intermediate good i. The resulting demand for intermediate good i from each of the households is

$$x_{it} = \left(\frac{P_{it}}{P_t}\right)^{-\theta_t} \gamma_t^{\theta_t - 1} y_t \tag{2}$$

for any $i \in [0,1]$. Inserting this demand into the production function (1) yields the final-good price

$$P_t = \left(\int_0^1 P_{it}^{1-\theta_t} di\right)^{\frac{1}{1-\theta_t}} \gamma_t^{-1} \tag{3}$$

which equals its marginal cost of production, since all households can compose identical final goods at identical cost. Aggregating intermediate-good demands (2) across households yields the aggregate demand for intermediate good i

$$X_{it} = \left(\frac{P_{it}}{P_t}\right)^{-\theta_t} \gamma_t^{\theta_t - 1} Y_t \tag{4}$$

where Y_t is the aggregate demand for final goods.

In each period t, intermediate-good producer i finds the optimal mix of inputs, capital k_{it}, labor n_{it} and land l_{it}, so as to minimize production costs $R_t k_{it} + W_t n_{it} + F_t l_{it}$ subject to its production technology $X_{it} = z_t k_{it}^{\alpha} n_{it}^{1-\alpha-\nu} l_{it}^{\nu}$, where W_t is the nominal wage, R_t is the nominal rental rate of capital, while F_t is the nominal rental rate of land. The weight each of these factors carry in production is determined by the coefficients $\alpha \in (0,1)$ and $\nu \in (0,1)$. As usual, $z_t > 0$ is an exogenous productivity shock. The first-order conditions from cost minimization yield producer i's factor demands

$$k_{it} = \alpha \frac{\lambda_t X_{it}}{R_t}, \tag{5}$$

$$n_{it} = (1 - \alpha - \nu) \frac{\lambda_t X_{it}}{W_t}, \tag{6}$$

$$l_{it} = \nu \frac{\lambda_t X_{it}}{F_t}, \tag{7}$$

where

$$\lambda_t = \frac{1}{z_t} \left(\frac{R_t}{\alpha}\right)^{\alpha} \left(\frac{W_t}{1-\alpha-\nu}\right)^{1-\alpha-\nu} \left(\frac{F_t}{\nu}\right)^{\nu} \tag{8}$$

is the marginal cost of producing intermediate goods.

In the absence of rigidities, imperfect information and anything else that interferes with price-setting, intermediate-good producer i chooses the price P_{it} that maximizes its period-t profits given the demand it faces (4), and thus maximizes $\Pi_{it} = (P_{it} - \lambda_t)\left(\frac{P_{it}}{P_t}\right)^{-\theta_t}\gamma_t^{\theta_t - 1}Y_t$ with respect to P_{it}, yielding

$$P_{it} = \frac{\theta_t}{\theta_t - 1}\lambda_t \tag{9}$$

a gross markup $\theta_t/(\theta_t - 1) \in (1, \infty)$ of its marginal cost of production λ_t. With menu costs, imperfect information, or any other distortion to price-setting, intermediate-good producer i will apply a potentially different markup ω_{it} to its marginal cost λ_t, so

$$P_{it} = \omega_{it}\lambda_t \tag{10}$$

where the markup ω_{it} can differ over time and across producers.

Inserting for the potentially distorted price (10) in the price aggregator (3), after substituting for the marginal cost of production (8), yields the aggregate price level

$$P_t = \gamma_t^{-1} z_t^{-1}\left(\frac{R_t}{\alpha}\right)^{\alpha}\left(\frac{W_t}{1-\alpha-\nu}\right)^{1-\alpha-\nu}\left(\frac{F_t}{\nu}\right)^{\nu}\left(\int_0^1 \omega_{it}^{1-\theta_t}di\right)^{\frac{1}{1-\theta_t}} \tag{11}$$

and the relative price

$$\frac{P_{it}}{P_t} = \gamma_t \frac{\omega_{it}}{\left(\int_0^1 \omega_{it}^{1-\theta_t}di\right)^{\frac{1}{1-\theta_t}}}. \tag{12}$$

Substituting this relative price into the demand function for intermediate good i (4), and inserting the resulting equation and the marginal production cost (8) into the factor demands (5), (6) and (7), and aggregating over all intermediate-good producers, we find the aggregate demands for capital, labor and land,

$$K_t = \gamma_t^{-1} z_t^{-1}\left(\frac{R_t}{\alpha}\right)^{\alpha-1}\left(\frac{W_t}{1-\alpha-\nu}\right)^{1-\alpha-\nu}\left(\frac{F_t}{\nu}\right)^{\nu} Y_t \frac{\int_0^1 \omega_{it}^{-\theta_t}di}{\left(\int_0^1 \omega_{it}^{1-\theta_t}di\right)^{\frac{-\theta_t}{1-\theta_t}}}, \tag{13}$$

$$N_t = \gamma_t^{-1} z_t^{-1}\left(\frac{R_t}{\alpha}\right)^{\alpha}\left(\frac{W_t}{1-\alpha-\nu}\right)^{-\alpha-\nu}\left(\frac{F_t}{\nu}\right)^{\nu} Y_t \frac{\int_0^1 \omega_{it}^{-\theta_t}di}{\left(\int_0^1 \omega_{it}^{1-\theta_t}di\right)^{\frac{-\theta_t}{1-\theta_t}}}, \tag{14}$$

$$L_t = \gamma_t^{-1} z_t^{-1} \left(\frac{R_t}{\alpha}\right)^{\alpha} \left(\frac{W_t}{1-\alpha-\nu}\right)^{1-\alpha-\nu} \left(\frac{F_t}{\nu}\right)^{\nu-1} Y_t \frac{\int_0^1 \omega_{it}^{-\theta_t} di}{\left(\int_0^1 \omega_{it}^{1-\theta_t} di\right)^{\frac{-\theta_t}{1-\theta_t}}}, \tag{15}$$

respectively.

3. EQUILIBRIUM

In addition to effortlessly composing final goods, households supply labor N_t, capital K_t and land L_t to the collectively owned intermediate-good producers in order to provide for consumption C_t and the accumulation of physical capital K_t and money M_t, solving a standard dynamic utility-maximization problem. To simplify, the supply of land is normalized to one. Equating aggregate demand for land (15) to its inelastic unitary supply yields the aggregate production function

$$Y_t = \gamma_t z_t K_t^{\alpha} N_t^{1-\alpha-\nu} \frac{\left(\int_0^1 \omega_{it}^{1-\theta_t} di\right)^{\frac{-\theta_t}{1-\theta_t}}}{\int_0^1 \omega_{it}^{-\theta_t} di} \tag{16}$$

after exploiting that the aggregate demands for factors of production (13)-(15) imply that $R_t/F_t = \alpha/(\nu K_t)$ and $W_t/F_t = (1-\alpha-\nu)/(\nu N_t)$, which guarantees an optimal factor mix in the production of intermediate goods.[4] Combining these two conditions with the one for the price level (11), yields

$$\frac{R_t}{P_t} = \alpha \gamma_t z_t K_t^{\alpha-1} N_t^{1-\alpha-\nu} \left(\int_0^1 \omega_{it}^{1-\theta_t} di\right)^{\frac{-1}{1-\theta_t}} \tag{17}$$

$$\frac{W_t}{P_t} = (1-\alpha-\nu)\, \gamma_t z_t K_t^{\alpha} N_t^{-\alpha-\nu} \left(\int_0^1 \omega_{it}^{1-\theta_t} di\right)^{\frac{-1}{1-\theta_t}} \tag{18}$$

$$\frac{F_t}{P_t} = \nu \gamma_t z_t K_t^{\alpha} N_t^{1-\alpha-\nu} \left(\int_0^1 \omega_{it}^{1-\theta_t} di\right)^{\frac{-1}{1-\theta_t}} \tag{19}$$

which are the real rental rates and real wage. Due to the lack of significance of land as a source of fluctuations, we let ν converge toward zero, so that land is eliminated from the model henceforth.

[4] Including land as an inelastically supplied input facilitates obtaining an explicit solution for aggregate output (16), since the production side only determines the optimal factor mix, not the levels. Below, we let the importance of land converge to zero.

4. TOTAL FACTOR PRODUCTIVITY

Aggregate output is ($\nu \to 0$)

$$Y_t = A_t K_t^{\alpha} N_t^{1-\alpha} \tag{20}$$

where total factor productivity

$$A_t = \gamma_t z_t \frac{\left(\int_0^1 \omega_{it}^{1-\theta_t} di\right)^{\frac{-\theta_t}{1-\theta_t}}}{\int_0^1 \omega_{it}^{-\theta_t} di} \tag{21}$$

depends on the level of the productivity shocks γ_t and z_t, but only on the dispersion in the markups ω_{it}. To see this, note that when all intermediate-good producers i apply the same markup ω_t, total factor productivity (21) simplifies to $A_t = \gamma_t z_t$ independently of the value of ω_t.

Intuitively, increased productivity $z_t \gamma_t$ for all producers of intermediate goods raises total factor productivity A_t, since more final goods Y_t can be produced with any given (strictly positive) quantities of capital and labor. A higher z_t makes capital and labor more efficient in the production of intermediate goods, while a higher γ_t raises the amount of final good that can be produced with a given quantity of intermediate goods. Because producers are a priori identical and face the same elasticity θ_t, they should all apply the same markup. When they do not, relative prices become distorted, which in turn makes the composition of the final good inefficient, resulting in less of it being produced for any given quantities of capital and labor. The level of the markups has no impact on relative prices, or the composition of final goods, so it has no effect on total factor productivity (as first noted by Lerner (1934)).

Observing the effects price rigidities have on total factor productivity empirically promises to be difficult. Productivity is affected by many variables, including the development and diffusion of new technologies. In addition, economic theory predicts that total factor productivity should impact most other variables, including those expected to be key in distorting price setting, such as inflation. Moreover, monetary policy responding to movements in output spurred by changes in productivity can obscure the impact variables such as inflation can have on productivity in the presence of nominal rigidities.

5. FACTOR MARKETS

The real rental rate of capital and real wage are ($\nu \to 0$)

$$\frac{R_t}{P_t} = \alpha K_t^{\alpha-1} N_t^{1-\alpha} Q_t \tag{22}$$

$$\frac{W_t}{P_t} = (1-\alpha)\, K_t^{\alpha} N_t^{-\alpha} Q_t \tag{23}$$

respectively, where

$$Q_t = \gamma_t z_t \left(\int_0^1 \omega_{it}^{1-\theta_t} di \right)^{\frac{-1}{1-\theta_t}} \tag{24}$$

captures the direct impact of distortions to price-setting. Without dispersion, $Q_t = \gamma_t z_t \omega_t^{-1}$, so it depends also on the average markup level.

Increased productivity $\gamma_t z_t$ for all producers raises total factor productivity A_t, and therefore also tends to raise factor prices, just as a regular positive productivity shock would. By leading to an inefficient mix of intermediate goods, distorted markups make capital and labor be used less efficiently in the production of final goods, which contributes to lowering the real wage and rental rate. In addition, some firms apply markups that are higher, and others apply markups that are lower, than they otherwise would, affecting the magnitude of the average markup. This impacts real factor prices because the higher the markup a producer applies, the lower its production, and the less inputs it demands, thus reducing factor prices. Whether the effect on real factor prices is positive or negative depends on the skewness of the distribution of the markups, and since firms that apply low markups become larger than those that apply high ones, the distribution needs to be positively skewed for the impact on factor prices to be negative (so that the producers that charge too much shrink by more than the growth of those that charge too little). When the distribution is not positively skewed to a sufficient extent, dispersion in markups can raise factor prices despite lowering total factor productivity. Combined with sufficiently elastic factor supplies, this can make aggregate output increase as the dispersion in markups grows, even if total factor productivity falls. An example of this is the inflation-output trade-off that arises in sticky-price models such as that proposed by Calvo (1983). Inflation distorts markups, which reduces total factor productivity, but at the same time producers that charge markups that are too low increase their sales so much that total output rises. Producing more when total factor productivity is low, is obviously costly in terms of household utility, providing a strong rationale for avoiding inflation. However, with price rigidities, such a rationale exists even without an inflation-output trade-off, since inflation temporarily reduces total factor productivity.

Distortions to price-setting that have a uniform effect on markups, not generating dispersion, have no effect on total factor productivity, and only affect aggregate output through the quantity of factors employed. Since these can lower or raise markups, such distortions can, in theory, contribute to raising or lowering aggregate output. By reducing markups, and the dead-weight loss of imperfect competition, distortions to price-setting can boost welfare if they raise output. When distortions affect the dispersion of markups, they lower total factor productivity, which always has a negative impact on welfare. Still, the total effect on welfare, aggregate output, and factor markets, can go either way.

The impact heterogeneous markups have on total factor productivity A_t and factor prices through Q_t, depends on the elasticity of substitution θ_t, which can vary over time. As a result, one should not expect the effects of markup heterogeneity to be constant over time. In particular, when it is inflation that generates the dispersion in the markups, one should not expect the inflation-output relationship to be a stable one, since in theory, even its sign could change, as the relative importance of the effects through A_t and Q_t vary with θ_t. This implies that testing the relevance of price rigidities empirically by studying output is futile. The same applies to factor demands and prices.

6. INCOME SHARES

The income share of labor is ($\nu \to 0$)

$$\frac{W_t N_t}{P_t Y_t} = (1-\alpha)\,\frac{\int_0^1 \omega_{it}^{-\theta_t} di}{\int_0^1 \omega_{it}^{1-\theta_t} di} = (1-\alpha)\,\frac{Q_t}{A_t} \tag{25}$$

which simplifies to

$$\frac{W_t N_t}{P_t Y_t} = \frac{1-\alpha}{\omega_t} \tag{26}$$

when markups are identical across intermediate-good producers. Hence, the share depends on both the level and dispersion of markups, but is independent of productivity. The income share of labor also depends on the value of α, and with heterogeneous markups, the elasticity of substitution θ_t (through A_t, Q_t and ω_{it}). The same applies to the income share of capital, which is

$$\frac{R_t K_t}{P_t Y_t} = \alpha\frac{\int_0^1 \omega_{it}^{-\theta_t} di}{\int_0^1 \omega_{it}^{1-\theta_t} di} = \alpha\frac{Q_t}{A_t} \tag{27}$$

so barring any changes in α, it should behave exactly the same as the income share of labor (25). Whatever income is not used to pay capital and labor goes to profits, so

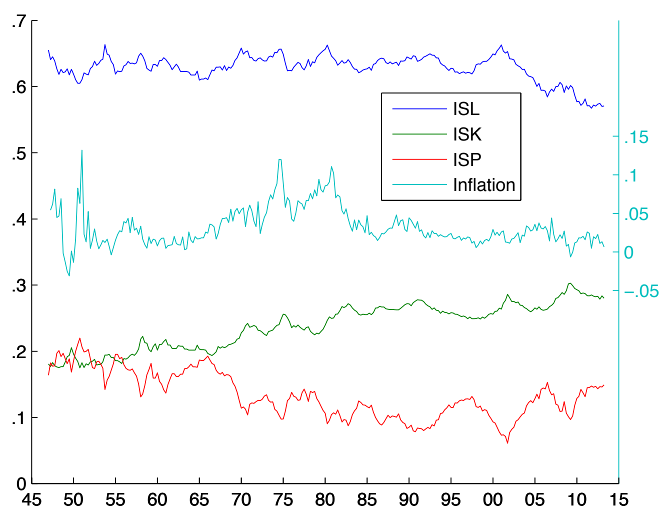
$$\frac{\Pi_t}{P_t Y_t} = 1 - \frac{\int_0^1 \omega_{it}^{-\theta_t} di}{\int_0^1 \omega_{it}^{1-\theta_t} di} = 1 - \frac{Q_t}{A_t} \tag{28}$$

is its income share.

Without distortions to price-setting, the income shares of labor, capital and profits simplify to $(1-\alpha)\omega_t^{-1}, \alpha\omega_t^{-1}$ and $1-\omega_t^{-1}$, respectively, where the markup $\omega_t = \theta_t/(\theta_t - 1)$, and the shares would only depend on θ_t (apart from the constant α). When θ_t increases, making the economy more competitive, producers charge lower markups, reducing the share of income that goes to profits, and raising those that go to labor and capital. When θ_t falls, the process is reversed. Hence, the income shares are affected by nominal price rigidities, but in the absence of these depend only on θ. This is a great advantage relative to output, productivity or factor use, which also depend on γ_t and z_t.

7. DATA

FIG. 1. Income shares and inflation, U.S. NFCB 1947-2013.



It is difficult to categorize different types of income into compensation for labor, capital and profits. However, the Bureau of Economic Analysis provides such a split-up for the U.S. nonfinancial corporate business (NFCB) sector, which historically has made up about half of total GDP.[5] Figure 1 plots these income shares between the first quarter of 1947 and the second quarter of 2013, together with the annualized quarterly rate of

[5]The data is available in NIPA table 1.15 at www.bea.gov. It is constantly revised, our version was downloaded November 2013.

inflation computed from the GDP deflator for the U.S. economy as a whole (right scale).[6] The income share of labor (ISL), or unit labor cost as it is labeled in the original data, has varied between 0.57 and 0.66. The income share of capital (ISK), which in the data encompasses everything that is not compensation of employees or profits, has risen from 0.18 to 0.30 over the period. The income share of profits (ISP) has been falling from a maximum of 0.22 in the 1950s, before flattening out in the 90s, varying between 0.06 and 0.15. The income shares of labor and capital are each negatively correlated with that of profits, particularly capital. Inflation is somewhat negatively correlated with the profit share, positively correlated with the labor share, and uncorrelated with the capital share. Basic statistics for the income shares is summarized in table 1.

TABLE 1.

Descriptive statistics for income shares, U.S. NFCB data.

Income share of	mean	SD	corr infl.	corr ISL	corr ISK
labor (ISL)	0.628	0.020	0.317	1.000	
captial (ISK)	0.238	0.034	−0.040	−0.228	1.000
profits (ISP)	0.133	0.035	−0.139	−0.343	−0.835

Regressing each of the income shares on inflation and a constant term yields a statistically significant negative coefficient for the impact of inflation on the profit share, and a significant positive coefficient for the labor share. These results are summarized in table 2, which also shows that inflation is not significant for the capital share.[7] The errors with which economic aggregates are measured can produce endogeneity and lead to biased and inconsistent estimates. Assuming such measurement errors are independent over time, they can be corrected for by using two-stage least squares with lags of both the dependent and independent variables as instruments. The estimates in table 2 were produced using TSLS using four lags of the variables and a constant as instruments.[8]

On average, a one percentage-point increase in inflation is associated with a 0.34 percentage-point drop in the profit share and similar gain in the labor share. Except for that of the capital share, these co-movements are consistent with price rigidities. However, they could also be caused

[6]See NIPA table 1.1.4 at www.bea.gov. Using the deflator for the nonfinancial corporate business sector does not alter our results, as it is highly correlated with that of GDP as a whole. The same applies to constructed measures of unanticipated inflation, which according to some of the theoretical models could have a greater impact on price-setting than anticipated inflation.

[7]As usual, the standard errors are provided in parenthesis, * denotes statistical significance at 10%, ** at 5% and *** at 1%.

[8]The ordinary least squares estimates for the impact of inflation on the income shares of labor, capital and profits are 0.252***, −0.055 and −0.196**, respectively.

TABLE 2.

Regressing income shares on inflation and a constant, TSLS, U.S. NFCB.

Income share of	constant	inflation	R^2
labor (ISL)	0.617 (0.002)***	0.360 (0.058)***	0.078
capital (ISK)	0.240 (0.004)***	−0.021 (0.101)	0.000
profits (ISP)	0.143 (0.004)***	−0.338 (0.104)***	0.023

by the income shares and inflation both responding to a third variable, such as changes in the degree of competition θ_t, which according to our model would affect the income shares in the absence of nominal rigidities (assuming α is constant). When the economy becomes more competitive, a smaller share of income goes to profits and a larger one goes to labor. Therefore, pinpointing the impact of price rigidities requires controlling for changes in competition. In order to do so, we need data on the overall degree of competition in the U.S. economy, but this cannot be measured from markups, since according to our model, price rigidities also affect these.[9] Elasticities of substitution and market shares are not available for the economy as a whole. Any aggregate measure of competition, such as the number of firms, hiring, bankruptcies, start-ups, or production, are very noisy measures of competition, since they are affected by all sorts of shocks, including those to productivity. Hence, our strategy is to use factor analysis to obtain a measure of competition to control for when measuring the impact inflation has on the income shares. In addition, the approach should permit controlling for anything else affecting the income shares, such as the degree of unionization, or variations in α.

8. FACTOR ANALYSIS OF INCOME SHARES

Factor analysis is usually used for data reduction, that is, to describe the co-movement of a large number of variables with a subset of underlying factors. Typically, these underlying factors are estimated and used as explanatory variables in regression equations. We do the same, except that instead of data reduction, we use the factors to distinguish between the effects that competition and inflation have on the income shares. We imagine that the income shares and rate of inflation are linearly dependent on four unobservable orthogonal factors. In the absence of price rigidities,

[9] Unit profits are sometimes used as an aggregate measure of markups and the degree of competition θ_t. However, according to our model, unit profits are affected by nominal rigidities and cannot distinguish between the effects of nominal rigidities and changes in competition.

the income shares should, according to our theoretical model, only depend on the degree of competition θ_t. With rigidities, they could also be influenced by inflation. In a more general framework, the income shares could also be affected by the degree of unionization, minimum wage laws, or variations in α. While the observed variables are assumed to depend linearly on the unobserved factors, they do not need to be linear in the underlying parameters θ_t or α. That is, the factor capturing competition does not need to equal θ_t, but could be a non-linear function of θ_t that affects the income shares in a linear fashion.[10]

TABLE 3.

Estimated orthogonal Varimax rotated factor loadings, U.S. NFCB.

	F1	F2	F3	F4
ISL	0.017	0.986	0.167	−0.005
ISK	0.969	−0.243	−0.025	0.029
ISP	−0.945	−0.319	−0.069	0.033
Inflation	0.022	0.154	0.988	−0.001
Cum. prop. var.	0.465	0.817	0.999	1.000

The estimated factor loadings based on the correlation matrix of the three income shares and inflation, rotated with the Varimax approach, are reported in table 3. Each of the four columns in the table contains each of the estimated factor loadings. The bottom row lists the cumulative proportion of the total (standardized) variance explained by each of the factors. In our case, the correlation between each factor and the original variable is practically identical to the estimated factor loadings, and is therefore not reported separately. The table shows that the first factor, which explains almost half of the variance in the original data, tends to lower the profit share and raise the capital share. The second factor, which explains 35% of the variance, has a positive effect on the labor share and a mild negative effects on the profit and capital shares. The main effect of the third factor, which explains 18% of the variation in the data, is on inflation. The fourth factor is negligible. From this, we infer that the third factor is capturing the effect of inflation, while factors one and two appear to be capturing the effects of competition, redistributing income from profits to capital and labor. It is worth noting that while our theoretical model suggests that competition should have the same impact on the labor and capital shares, the data suggests otherwise. A plausible explanation is that there is more than just competition in final goods that affects the

[10] Applying the logarithm to the income shares, which according to our theoretical model should make those for labor and capital linear in terms of the underlying variables A_t and Q_t, or ω_t in the absence of price rigidities, does not alter our results.

income shares, and that these forces affect labor and capital differently. Some examples are minimum wage laws and unionization versus the market power of capital-good suppliers.

With the third factor representing inflation, the remaining ones can be used to control for changes in competition, and other contingencies affecting the income shares, while regressing these on actual inflation. Table 4 provides the results. Since the factors have been constructed so that their linear combinations represent the data perfectly, and inflation is almost perfectly correlated with the third factor, the fit of the regressions is almost perfect, making the standard errors close to zero. As a result, all the estimated coefficients appear as statistically significant, though this is artificial, as it comes from treating the factors as observed variables, instead of estimated ones.[11] Inflation is associated with an increase in the labor share, and a fall in the shares of profits, and to a much smaller extent, of capital. In particular, a one percentage-point increase in inflation tends to raise the labor share by 0.13 percentage-points, lower the profit share by 0.1 points and reduce the capital share by 0.04 points.[12] These results are in line with our initial estimates (table 2), but show that controlling for changes in competition reduces the estimated impact of inflation to about a third for the income shares of labor and profits. This is consistent with the predictions of our theoretical model, since changes in competition can generate co-movements indistinguishable from those produced by inflation in an economy with price rigidities. However, controlling for competition actually raises the estimated impact of inflation on the capital share, which is somewhat puzzling.

TABLE 4.

Regressing income shares on inflation, controlling for other factors, U.S. NFCB.

Income share of	constant	F1	F2	inflation	F4
labor (ISL)	0.624	0.000	0.019	0.134	−0.000
capital (ISK)	0.239	0.033	−0.008	−0.035	0.001
profits (ISP)	0.137	−0.033	−0.011	−0.099	0.001

The results remain unchanged when regressing the income shares on the four factors (using $F3$ instead of inflation). The factors are by construction orthogonal, so eliminating any of them from the regressions does not introduce any bias in the estimates, leaving them as reported in table 4. However, doing so reduces efficiency, resulting in higher standard errors.

[11] Of course, all national income data is estimated.

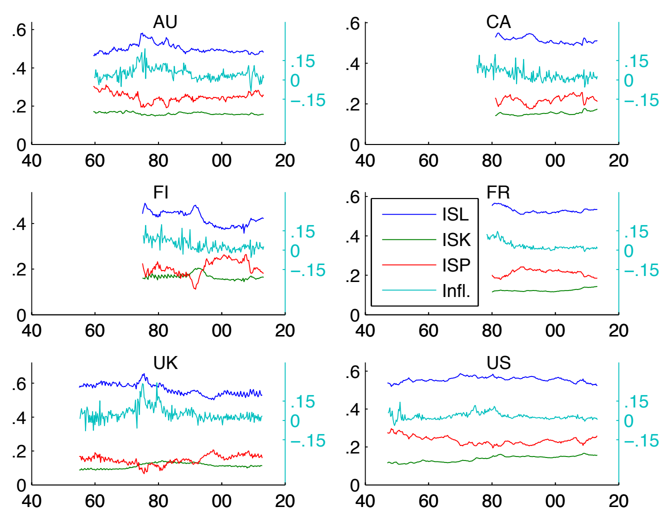
[12] Ordinary and two-stage least squares give exactly the same results in this case, so either measurement error has no impact on the estimates, or it is correlated over time and therefore not corrected for by instrumenting with lags.

Still, when regressing the income shares on just a constant and $F3$, mimicking table 2, $F3$ remains significant for both the labor and profit shares.

9. INTERNATIONAL EVIDENCE

The OECD provides quarterly national income account data for more than thirty countries. However, the data is not structured into income shares for labor, capital and profits as above. Instead, it is grouped into compensation of employees, consumption of fixed capital, net operating surplus and taxes and subsidies. The net operating surplus category includes profits, proprietor's income and rental income, and thus potentially compensation to both capital and labor. Since the data for each of the subcategories is not available, we use the compensation of employees as the labor share, consumption of fixed capital as the capital share and net operating surplus as the profit share, all as fractions of gross national income. For comparison, we redo the analysis for the U.S. with this more rudimentary division of income, and obtain similar results as with the data from the nonfinancial corporate business sector.

FIG. 2. Income shares and inflation for Australia, Canada, Finland, France, U.K. and U.S.



Another problem with the OECD data is that for most countries there is less than 25 years of observations. Usually, this is because the countries do not have quarterly GDP data using the income approach going further back, or that this data is not available on-line. For Australia it goes back to 1959, Canada 1981, Finland 1975, France 1980, U.K. 1955 and U.S. 1947.[13] For the remaining countries the series start anywhere between 1988 and 2000, so these were discarded for having too few observations.[14] The international data is plotted in figure 2 and summarized in table 5, which shows that the average fraction of income actually included varies from 80 to 93%. The income shares of labor are positively correlated with inflation in all six countries, though more strongly so in some than others. The profit shares are negatively correlated with inflation in all but Canada. The income shares of capital are negatively correlated with inflation, except for Finland and the U.K. The income shares of labor and profits are negatively correlated for all the countries, while the correlation between the income shares of capital and profits vary. The data for the U.S. differs considerably from that for the U.S. nonfinancial corporate business sector. In particular, the labor and profit shares are significantly larger, while the capital share is smaller.

The results from regressing each of the income shares on inflation and a constant term for each of the six countries, using two-stage least squares, is summarized in table 6, which reports the coefficient on inflation for each of the income shares and countries. Inflation has a statistically significant positive impact on the labor share of income in all the countries, and a statistically significant negative impact on the profit share for all, except Canada where it is is not significant. The impact on the capital share is positive for the U.K., negative for Australia and Canada, and not significantly different from zero for Finland, France and the U.S. On average, a one percentage-point increase in inflation is associated with a rise in the income share of labor of anywhere from 0.34 to 0.77 percentage-points. The impact on the profit share varies from -0.32 to -0.58, while that on capital varies from 0.17 to -0.29. The redistributed income does not sum to one for each of the countries since the income shares themselves do not sum to one (due to taxes and subsidies, which are not allocated to any of the three income shares studied).

Because changes in the degree of competition, as well as other variables, could be generating the co-movements reported in table 6, we again derive controls for these using factor analysis. The estimated factor loadings based on the correlation matrix of the three income shares and inflation for each of the six countries, rotated with the Varimax approach, are reported in table 7. The table also includes the cumulative proportion of the variance (CPV)

[13]The data for the U.S. is actually from the BEA (www.bea.gov), for the U.K. it is from the Office for National Statistics (www.ons.gov.uk), while that for Finland is from Statistics Finland (www.stat.fi). These data sources are used since they go further back than in the OECD database.

[14]We estimate up to 22 parameters for each country, so anything less than 25 years of quarterly data seems inadequate.

TABLE 5.

Descriptive statistics for income shares, international data.

Country	variable	mean	SD	corr infl.	corr ISL	corr ISK
AU	ISL	0.501	0.025	0.571	1	
	ISK	0.161	0.006	−0.293	−0.309	1
	ISP	0.248	0.023	−0.387	−0.799	0.383
CA	ISL	0.514	0.016	0.144	1	
	ISK	0.153	0.008	−0.342	−0.274	1
	ISP	0.220	0.019	0.128	−0.814	−0.042
FI	ISL	0.423	0.032	0.463	1	
	ISK	0.167	0.013	0.047	0.614	1
	ISP	0.206	0.034	−0.188	−0.861	−0.749
FR	ISL	0.529	0.015	0.793	1	
	ISK	0.124	0.007	−0.214	0.141	1
	ISP	0.214	0.016	−0.484	−0.843	−0.577
UK	ISL	0.564	0.032	0.451	1	
	ISK	0.113	0.015	0.309	−0.256	1
	ISP	0.148	0.027	−0.597	−0.417	−0.693
US	ISL	0.556	0.014	0.434	1	
	ISK	0.138	0.016	−0.004	0.101	1
	ISP	0.235	0.020	−0.319	−0.647	−0.805

TABLE 6.

Regressing income shares on inflation and constant, TSLS, international data.

Income share of	AU	CA	FI	FR	UK	US
labor (ISL)	0.662***	0.340***	0.765***	0.446***	0.518***	0.400***
capital (ISK)	−0.066***	−0.286***	0.058	−0.047*	0.174***	0.022
profits (ISP)	−0.445***	0.073	−0.381***	−0.317***	−0.576***	−0.470***
Observations	215	129	153	134	231	265

explained by each of the factors. As above, we find that for each country, one of the factors aligns closely with inflation, being highly correlated with it.[15] The factor that explains the most variation in each of the six countries is the one that reallocates income between profits and labor (and to some degree, depending on the country, also capital). This differs from the U.S. NFCB data, where the first factor redistributes between capital and profits, while the second redistributes income between labor and profits (though the two explain similar fractions of the variation in the NFCB data, 46.5% versus 35.2%). In most of the countries in our sample, the inflation factor is the third most important one, explaining between 4% and 16% of the total variation. In Canada and Finland it is the second most important factor, explaining 35% and 25% of the variation, respectively.

Regressing each of the income shares in each of the countries on inflation and the remaining three control factors yields the results in table 8, which reports the estimated impact of inflation on each of the income shares for each of the countries. As above, we find that controlling for other variables that affect the income shares greatly reduces the estimated impact of inflation. It does so to between 17-63% of the original estimates for labor, 11-93% for profits and 5-74% for capital. On average, these estimates drop to 33%, 47% and 36% of the TSLS estimates without controls, for the income shares of labor, capital and profits, respectively. However, inflation still has a statistically significant positive impact on the income share of labor and a statistically significant negative impact on the profit share, with the exception of Canada, where inflation has a positive impact on the profit share. This outlier is somewhat puzzling, however, Canada is also the country for which we have the shortest sample. The impact of inflation on the capital share is negative for all countries, except the U.K. Regressing the income shares on just the inflation factor and a constant, mimicking table 6, yields statistical significance for inflation on the labor shares in all the countries, and on the capital shares in Australia, France, U.K. and U.S. (the estimates remain as in table 8). The inflation factor only remains statistically significant for capital in the U.K.

Contrary to what our theoretical model predicts, inflation appears to affect the income shares of labor and capital quite differently. This may be due to the difficulty in distinguishing payments to capital from profits in the original national accounts. If the capital share includes too many components that are really profits, the impact of inflation might be dampened, or could even change sign. The same could occur with the labor share, however, payments to labor are usually easier to distinguish from those to capital, due to the ownership structure. It is more common for the re-

[15]As above, the factor loading between the inflation factor and the inflation variable equals the correlation coefficient between the two. Hence, for Australia this correlation is 0.96, Canada 0.99, Finland 0.99, France 0.92, U.K. 0.94 and U.S. 0.98.

TABLE 7.

Estimated orthogonal Varimax rotated factor loadings, international data.

Country		ISL	ISK	ISP	Inflation	CPV
AU	F1	−0.534	0.161	0.919	−0.161	0.604
	F2	−0.121	0.975	0.195	−0.133	0.799
	F3	0.329	−0.125	−0.160	0.957	0.959
	F4	0.769	−0.083	−0.302	0.200	1.000
CA	F1	−0.929	0.056	0.969	0.007	0.464
	F2	0.112	−0.175	0.105	0.985	0.809
	F3	−0.197	0.983	−0.073	−0.173	0.971
	F4	0.291	−0.028	0.209	0.022	1.000
FI	F1	0.870	0.390	−0.866	0.159	0.649
	F2	0.328	−0.010	−0.057	0.987	0.903
	F3	0.300	0.921	−0.449	−0.006	0.979
	F4	0.213	0.007	0.214	0.013	1.000
FR	F1	0.819	0.183	−0.819	0.364	0.622
	F2	0.071	0.973	−0.479	−0.157	0.950
	F3	0.553	−0.139	−0.282	0.918	0.991
	F4	0.133	−0.003	0.141	−0.017	1.000
UK	F1	0.931	−0.042	−0.805	0.291	0.559
	F2	−0.254	0.985	−0.391	0.173	0.868
	F3	0.243	0.158	−0.302	0.940	0.984
	F4	0.094	−0.053	0.328	−0.037	1.000
US	F1	0.972	0.103	−0.794	0.215	0.565
	F2	0.007	0.994	−0.572	−0.002	0.847
	F3	0.231	−0.024	−0.152	0.977	0.996
	F4	0.043	−0.002	0.140	−0.005	1.000

TABLE 8.

Regressing income shares on inflation, controlling for other factors, international data.

Income share of	AU	CA	FI	FR	UK	US
labor (ISL)	0.184	0.059	0.229	0.283	0.148	0.127
capital (ISK)	−0.018	−0.048	−0.003	−0.035	0.046	−0.015
profits (ISP)	−0.083	0.068	−0.043	−0.160	−0.156	−0.126

cipients of the profits to be the owners of the physical capital (indirectly through the corporation), than for them to be employees of the corporation. Another explanation could be that wages are adjusted for inflation to a greater extent than profits and payments to capital, for example due to indexing. In this case, inflation would have an impact on the aggregate real economy directly through real factor prices, instead of through rigidities in output prices. In fact, the asymmetric effects on the income shares of labor and capital in our estimates could be an indication that nominal rigidities in factor markets might be more relevant at the aggregate level than those affecting the prices of goods.

Looking at the data, one might be concerned that our estimates are shaped by stochastic trends in the income shares and inflation, in particular for the shorter time series of Canada, Finland and France. To check for this, we reestimate the impact inflation has on the income shares after taking the first difference of the shares, inflation and the computed factors. Doing so confirms our previous estimates. That is, regressing the growth rate of the income shares on the growth rate of inflation and the remaining factors yields the same results as when the income shares are regressed on inflation and the other factors in levels. As with the U.S. NFCB data, when controlling for other factors, we obtain the same results whether we use two-stage or ordinary least squares.

10. CONCLUSIONS

The main caveat with our approach is that it is not always possible to distinguish exactly what each of the underlying factors that factor analysis generates represents. In our case, the correlation between the inflation factor and inflation is so high (0.92-0.99), that there is little doubt. In addition, we get identical results when replacing the original inflation measure with the inflation factor, while leaving the other factors as controls. However, it is unclear exactly what the remaining factors represent, and which one is capturing competition. Fortunately, what we are interested in, inflation, happens to be clearly identifiable, but there is nothing in our method that guarantees this. Rotating the factors facilitates their interpretation, but can at the same time appear somewhat arbitrary, since mathematically, any orthogonal rotation is just as good as another. Because of this, we use an approach (Varimax) where the rotation is entirely determined by the data.

We find that inflation does indeed have a positive impact on the income share of labor and a negative one on the share of profits, though the effect is smaller than what we find without controlling for competition. The impact on the capital share is negative, except for the U.K., which is contrary to what our model suggests it should be. This may reflect the fact that it is particularly difficult to distinguish between payments to capital and profits in national income accounts, or that nominal rigidities in factor markets are more important for the aggregate income shares than those affecting the prices of goods. While our evidence of non-neutrality is compatible with the existence of an inflation-output trade-off, it does not necessarily imply that such a trade-off exists.

APPENDIX: THE ORTHOGONAL FACTOR MODEL

Factor analysis seeks to describe the covariances, or correlations, among a group of observable variables in terms of a few underlying unobservable variables called factors.[1] Let p observable random variables be represented by the $p\times 1$ vector $\mathbf{X}$. The factor model postulates that $\mathbf{X}$ is linearly dependent upon $m \leq p$ unobservable orthogonal common factors $\mathbf{F_1}, \mathbf{F_2}, \ldots, \mathbf{F_m}$ and p errors, or specific factors $\boldsymbol{\epsilon_1}, \boldsymbol{\epsilon_2}, \ldots, \boldsymbol{\epsilon_p}$, so that

$$\mathbf{X} - \boldsymbol{\mu} = \mathbf{LF} + \boldsymbol{\epsilon} \tag{A.1}$$

where $E(\mathbf{X}) = \boldsymbol{\mu}$, $\mathbf{L}$ is the $p \times m$ matrix of factor loadings, $\mathbf{F}$ is the $m \times 1$ vector of factors and $\boldsymbol{\epsilon}$ is the $p \times 1$ vector of errors. The model assumes $E(\mathbf{F}) = \mathbf{0}, E(\mathbf{FF'}) = \mathbf{I_m}, E(\boldsymbol{\epsilon}) = \mathbf{0}$, $E(\boldsymbol{\epsilon\epsilon'}) = \boldsymbol{\Psi} = \mathrm{diag}(\psi_1, \psi_2, \ldots, \psi_p)$ and $E(\boldsymbol{\epsilon}\mathbf{F'}) = \mathbf{0}$, making the factors and errors orthogonal both within and across the two groups. Supposing the covariance matrix $E(\mathbf{X}-\boldsymbol{\mu})(\mathbf{X}-\boldsymbol{\mu})' = \boldsymbol{\Sigma}$, it follows that

$$\boldsymbol{\Sigma} = \mathbf{LL'} + \boldsymbol{\Psi} \tag{A.2}$$

from the assumptions above. For any orthogonal $m \times m$ matrix $\mathbf{Q}$, such that $\mathbf{QQ'} = \mathbf{Q'Q} = \mathbf{I_m}$, $\mathbf{LQ}$ and $\mathbf{Q'F}$ satisfy the same assumptions as $\mathbf{L}$ and $\mathbf{F}$ above, respectively, and generate the same covariance matrix $\boldsymbol{\Sigma}$, even though $\mathbf{LQ} \neq \mathbf{L}$ and $\mathbf{Q'F} \neq \mathbf{F}$. Algebraically, such a transformation rotates the coordinate axes, and can align the factors more closely to the observable variables, thus making these easier to interpret. We use the Varimax rotation, the most common algorithm. It makes the rotation be determined entirely by the data, and seeks to maximize the variance of the squared loadings of a factor (column) on all the variables (rows) in $\mathbf{L}$, so that a factor will tend to have either large or small loadings on any particular variable (see Kaiser (1958)).

Letting $\boldsymbol{\Sigma}$ have eigenvalue-eigenvector pairs $(\lambda_i, \mathbf{e_i})$ with $\lambda_1, \lambda_2, \ldots \lambda_p \geq 0$, spectral decomposition provides the factoring

$$\boldsymbol{\Sigma} = \lambda_1 \mathbf{e_1 e_1'} + \lambda_2 \mathbf{e_2 e_2'} + \cdots + \lambda_p \mathbf{e_p e_p'} \tag{A.3}$$

[1] This section borrows heavily from Johnson and Wichern (1992), which provides further details.

which yields $\mathbf{L} = [\sqrt{\lambda_1}\mathbf{e_1}, \sqrt{\lambda_2}\mathbf{e_2}, \ldots, \sqrt{\lambda_p}\mathbf{e_p}]$ and $\mathbf{\Psi} = \mathbf{0}$, making the errors, or specific factors, superfluous.[2] As a result, we have

$$\mathbf{X} - \boldsymbol{\mu} = \mathbf{LF} \tag{A.4}$$

where $\mathbf{L}$ is a square matrix, and the factor scores are given by

$$\mathbf{F} = \mathbf{L}^{-1}(\mathbf{X} - \boldsymbol{\mu}) \tag{A.5}$$

when $\mathbf{L}^{-1}$ exists. Computing the eigenvalue-eigenvector pairs $(\hat{\lambda}_i, \hat{\mathbf{e}}_\mathbf{i})$ of the sample covariance matrix $\mathbf{S}$, yields the estimated factor loadings $\hat{\mathbf{L}} = [\sqrt{\hat{\lambda}_1}\hat{\mathbf{e}}_\mathbf{1}, \sqrt{\hat{\lambda}_2}\hat{\mathbf{e}}_\mathbf{2}, \ldots, \sqrt{\hat{\lambda}_p}\hat{\mathbf{e}}_\mathbf{p}]$.[3] The estimated factor scores $\hat{\mathbf{F}}$ can then be computed using the estimated factor loadings $\hat{\mathbf{L}}$ through

$$\hat{\mathbf{F}} = \hat{\mathbf{L}}^{-1}(\mathbf{X} - \hat{\boldsymbol{\mu}}) \tag{A.6}$$

where $\hat{\boldsymbol{\mu}}$ is the estimated mean of the observable variables $\mathbf{X}$. Since the trace $tr(\mathbf{S}) = \hat{\lambda}_1 + \hat{\lambda}_2 + \cdots + \hat{\lambda}_p$, the ratio $\hat{\lambda}_i/(tr(\mathbf{S}))$ is used to measure the fraction of the total variance in $\mathbf{S}$ explained by factor i.

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[2] If one or more of the $\lambda_i \mathbf{e_i}\mathbf{e_i}'$ are close to zero, they can be dropped without affecting the sum above (A.3), and the covariance matrix can be represented almost perfectly with the number of factors m being less than that of the original variables p. Hence, when $m < p$, $\mathbf{\Psi}$ is the sum of the dropped $\lambda_i \mathbf{e_i}\mathbf{e_i}'$ terms. In this case, estimating the factor scores is more complicated than described here, see Johnson and Wichern (1992) for some approaches.

[3] In practice, the analysis is usually performed on the standardized values of the observable variables, as the results can be sensitive to the scaling. Hence, in terms of the original variables the analysis seeks to represent the correlation instead of the covariance.

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