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Essays on two contemporary topics through an intergenerational lens: smart technologies and economic sanctions

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ESSAYS ON TWO CONTEMPORARY TOPICS THROUGH AN INTERGENERATIONAL LENS: SMART TECHNOLOGIES AND ECONOMIC SANCTIONS

by

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Para ti no habrá sol, para ti no habrá muerte, para ti no habrá dolor, para ti no habrá calor, ni sed, ni hambre, ni lluvia, ni aire, ni enfermedad, ni familia.
Nada te causará temor, todo ha terminado para ti, excepto una cosa: hacer tu trabajo.
En el puesto que has sido asignado, ahí te quedarás para la defensa de tu nación, de tu gente, de tu raza, de tus costumbres, de tu religión.
Juras cumplir con el divino mandato!
Ehui!

Juramento Yaqui (Yaqui Oath)

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ABSTRACT

This thesis centers its scope on the macroeconomic implications of two contemporary issues affecting welfare: the arrival of smart technologies and global control policies as sanctions. The key element that integrates these topics into the thesis is the intergenerational perspective. The thesis employs overlapping generations (OLG) models to study how smart technologies could modify long-term economic conditions and how fiscal policies are to be thought as a global matter rather than isolated decisions. The first chapter addresses the circumstances under which smart technologies may drive people out of well-compensated work. The Chapter uses a two-period OLG model comprising two type of workers, high and low-tech, and two goods a capital intensive one and a labor intensive one. Automation, characterized as legacy code, combines with capital to give birth to a smart machine: a robot. In turn, as automation capacity grows these robots leave future workers both high and low-tech worse off. The lower code relative to capital increases the high-tech workers compensation, savings, and capital formation. However, as code accumulates, de-

mand for high-tech labor falls, limiting younger generations savings and investments. Similarly, the second chapter seeks to answer whether robots raise or lower economic well-being. The setup is once again a two-period OLG. However, in this economy two goods are produced and consumed, but only one is fully automatable. Robots may be harmful except when robotic productivity is high enough that induces a virtuous circle of rising wages, savings, and output, producing the open-ended constant growth of an AK model. Additionally, a government transfer can turn an increase in robotic productivity into a long-term welfare improvement for future generations. Finally, the third chapter develops a large-scale multi-country OLG model to address the fiscal implications of global sanctions to a country namely Russia. The model is uniquely suited to understanding the long-term effect of different trade and fiscal regimes. The sanctioned country responds either by seizing foreign assets, or imposing capital controls, policies that might hurt the sanctioning countries. In all scenarios, except for the most benign, all generations alive at the time are made worse off in the sanctioned country.

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List of Abbreviations

BLS	....	Bureau of Labor Statistics
BEA	....	Bureau of Economic Analysis
CES	....	Constant Elasticity of Substitution
GDP	....	Gross Domestic Product
GFS	....	Government Finance Statistics
IMF	....	International Monetary Fund
NIPA	....	National Institute of Pension Administrators
OECD	....	Organization for Economic Cooperation and Development
OLG	....	Overlapping Generation
R&D	....	Research and Development
UN	....	United Nations
WB	....	World Bank
WDI	....	World Development Indicators
WEO	....	World Economic Outlook

Chapter 1

Introduction

Through the years of my doctoral studies I found myself facing a large range of possibilities to choose as main research field. I found fascinating the econometric world as presented by Pierre Perron and Zhongjun Qu. Probably one of the best classes I have ever taken was Larry Epstein's general equilibrium. The macroeconomics roster of professors was great too. Bob King, Simon Gilchrist, and Christophe Chamley were the perfect spice for the diverse range of macro topics. I could not walk away from a personal interest, the open economy, and my mentor here, Marianne Baxter, was and will be the main influence on my understanding of how the world dynamics work.

It was, though, in the third floor of 270 Bay State Road were my formal research began. I had the opportunity to work in topics that really interested me and had an adviser who supported me and who always made me think beyond boundaries to make a simple idea a great research idea. The policy: one paper one idea; the adviser: Larry Kotlikoff, my friend and coauthor. The research journey brought a key player into the research team. Seth G. Benzell the only other student attending the public finance class. We found a large intersection of research tastes and a common interest on pursuing them with Larry. The thesis is then about walking towards the journey of two fascinating topics: smart technologies and global policies.

Robots, automation, smart technologies, will they change world in the same way the industrial revolution did? In a series of two papers, my coauthors and I think that this time might be slightly different. In fact, the two initial papers of this thesis develop models that incorporate production technologies that operate with smart machines, or robots. However, these technologies could permanently hurt workers, either by sending them to lower paid jobs or to simply put them out of jobs. One of the key elements is the use of a life-cycle approach instead of an infinitely lived representative agent. The reason is that by separating agents into cohorts with different choices is useful to support one of our main messages: as smart techs are largely used, if positive spillovers are not accounted, there might be distributional wealth shift against future workers. In our model, workers who enjoy of the fruits of the advances grow old and live a better life. However, younger generations face a fierce competition between their labor supply and the productivity of the automated processes that could substitute them. The second chapter studies the role of robots in substituting production lines. As robots become more productive firms find enough incentives to switch from only using a traditional technology to one that combines both types. This unambiguously affects labor as job posts fall. However, when robotic productivity is high enough to abandon the traditional technology, the economy enters in a growth pattern such the one observed in an AK model with benefits for all future generations. Here the positive effect on wages of high non-automatable good prices dominates.

In the last chapter I change gears to study my second subject of interest. It forms part of a personal research agenda about global fiscal policies. In facto, during the third and fourth year of the doctoral program I had the opportunity to work with great colleagues from the Gaidar Institute in Moscow. It coincided with the "Western" economies imposing sanctions to Russia. So, the third chapter presents a model where the 6 largest economies interact by trading goods and capital with each other. It is based on a life-cycle approach that allow us to consider demographic, health, education, and pension profiles. The model is large scale as it includes 91 generations for each country. The sanction scenario correspond to an extreme case where all countries impose stringent sanctions on Russia such that they send the country into a state of autarky. The main assumptions here is that Russia will remain committed to maintain a sustainable fiscal balance. Thus, Russia will levy taxes on household and workers to compensate for the forgone revenues due to trade restrictions. Russia can respond. We simulate a scenario were Russia seizes domestic assets from foreign investors. Certainly, this reduces the losses in welfare but the sanctions will still require high taxation to keep the public finances stable.

The thesis is structured the following way. First, Robots are Us: Some Economics of Human Replacement presents a model where legacy code and physical capital give birth to a robot that may send workers to lower wages jobs. The second chapter, Robots: Curse or Blessing, shows a two-sector model where only one of them can be fully automated by robots. The third chapter, Can Russia Survive Economic Sanctions? exposes the large-scale OLG where Russia is sent into a state of autarky. Finally, the conclusion groups the lessons extracted from each chapter.

Chapter 2

Robots Are Us: Some Economics of Human Behavior[1]

Whether it's bombing our enemies, steering our planes, fielding our calls, rubbing our backs, vacuuming our floors, driving our taxis, or beating us at Jeopardy, it's hard to think of hitherto human tasks that smart machines can't do or won't soon do. Few smart machines look even remotely human. But they all combine brains and brawn, namely sophisticated code and physical capital. And they all have one ultimate creator us.

Will human replacement - the production by ourselves of ever better substitutes for ourselves - deliver an economic utopia with smart machines satisfying our every material need? Or will our self-induced redundancy leave us earning too little to purchase the products our smart machines can make?

Ironically, smart machines are invaluable for considering what they might do to us and when they might do it. This paper uses the most versatile of smart machines a run-of-the-mill computer to simulate one particular vision of human replacement. Our simulated economy an overlapping generations model – is bare bones. It features two types of workers consuming two goods for two periods. Yet it admits a large range of dynamic outcomes, some of which are quite unpleasant.

The model's two types of agents are called high-tech workers and low-tech workers. The first group has a comparative advantage at analytical tasks, the second in empathetic and interpersonal tasks. Both work full time, but only when young. High-tech workers produce new software code, which adds to the existing stock of code. They are compensated by licensing their newly produced code for immediate use and by selling rights to its future use. The stock of code – new plus old – is combined with the stock of capital to produce automatable goods and services (hereafter referred to as 'goods'). Goods can be consumed or used as capital. Unlike high-tech workers, low-tech workers are right brainers artists, musicians, priests, astrologers, psychologists, etc. They produce the models other good, human services (hereafter referred to as 'services'). The service sector does not use capital as an input, just the labor of high and low-tech workers.

Code references not just software but, more generally, rules, instructions, and associated data for generating output from capital. Because of this, code is both created by and is a substitute for the analytical labor provided by high-tech workers in the good (autmomatable) sector. Code is not to be thought of as accumulating in a quantitative way (anyone who has worked on a large software project can testify that fewer lines of code often mean a better program) but rather in efficiency units. Code accumulation may be a result of programmers typing out code directly, of machine learning systems getting better at a task under the supervision of human trainers[2], or of innovation in designing learning algorithms themselves. In the United States, more than 5 percent of total wages is paid to those engaged in computer or mathematical occupations[3]; a much larger share of compensation is being paid to those engaged in creating code broadly defined.

Code needs to be maintained, retained, and updated. If the cost of doing so declines via, for example, the invention of the silicon chip, the model delivers a tech boom, which raises the demand for new code. The higher compensation received by high-tech workers to produce this new code engenders more national saving and capital formation, reinforcing the boom. But over time, as the stock of legacy code grows, the demand for new code and, thus for high-tech workers, falls.

The resulting tech bust reflects past humans obsolescing current humans. This process explains the choice of our title, *Robots Are* ***Us***. The combination of code and capital that produce goods constitutes, in effect, smart machines, aka robots. And these robots contain the stuff of humans – accumulated brain and saving power. Take Junior – 2013's World Computer Chess Champion. Junior can beat every current and, possibly, every future human on the planet. Consequently, his old code has largely put new chess programmers out of business.

Once begun, the boom-bust tech cycle can continue if good producers switch technologies la (Zeira, 1998) in response to changes over time in the relative costs of code and capital. But whether or not such Kondratieff waves materialize, tech busts can be tough on high-tech workers. In fact, high-tech workers can start out earning far more than low-tech workers, but end up earning far less.

Furthermore, robots, captured in the model by more code-intensive good production, can leave all future high-tech workers and, potentially, all future low-tech workers worse off. In other words, technological progress can be immiserating. This finding echoes that of (Sachs and Kotlikoff, 2012). Although our paper includes different features from those in (Sachs and Kotlikoff, 2012), including two sectors, accumulating code stocks, endogenous technological change, property rights to code, and boom-bust cycle(s), the mechanism by which better technology can undermine the economy is the same. The eventual decline in high-tech worker and, potentially, low-tech worker compensation limits what the young can save and invest. This means less physical capital available for next periods use. It also means that good production can fall over time even though the technological capacity to produce goods expands.

The long run in such cases is no techno-utopia. Yes, code is abundant. But capital is dear. And yes, everyone is fully employed. But no one is earning very much. Consequently, there is too little capacity to buy one of the two things, in addition to current consumption, that todays smart machines (our model's non-human dependent good production process) produce, namely next periods capital stock. In short, when smart machines replace people, they eventually bite the hands of those that finance them.

These findings assume that code is excludable and rival in its use. But we also consider cases in which code is non-excludable, non-rival, or both. Doing so requires additional assumptions but lets us consider the requirement that all code be open source, i.e., non-excludable. Surprisingly, such freeware policies can worsen long-run outcomes.

Our paper proceeds with some economic history – Ned Ludds quixotic war on machines and the subsequent Luddite movement. As section 2 indicates, Ludds instinctive fear of technology, ridiculed for over a century, is now the object of a serious economic literature. Section 3 places our model within a broader framework of human competition with robots to indicate what we, for parsimony's sake, exclude. Section 4 presents our model and its solution method. Section 5 illustrates the surprising range of outcomes that even this simple framework can generate. Section 6 considers how the nature of code ownership and rivalry affects outcomes. Section 7 follows (Zeira, 1998) in letting the choice of production technique respond to relative scarcity of inputs, in our case capital and code. Section 8 extends the model to allow for directed technological change – workers are allowed to create software that substitutes for capital instead of labor. Section 9 considers some potentially supporting evidences. Section 10 concludes.

2.1 Background and Literature Review

Concern about the downside to new technology dates at least to Ned Ludds destruction of two stocking frames in 1779 near Leichester, England. Ludd, a weaver, was whipped for indolence before taking revenge on the machines. Popular myth has Ludd escaping to Sherwood Forest to organize secret raids on industrial machinery, albeit with no Maid Marian.

More than three decades later in 1812, 150 armed workers – self-named Luddites marched on a textile mill in Huddersfield, England to smash equipment. The British army promptly killed or executed 19 of their number. Later that year the British Parliament passed The Destruction of Stocking Frames, etc. Act, authorizing death for vandalizing machines. Nonetheless, Luddite rioting continued for several years, eventuating in 70 hangings.

Sixty-five years later, (Marx, 1887) echoed Ned Ludd's warning about machines replacing humans.

> *Within the capitalist system all methods for raising the social productivity of labour are put into effect at the cost of the individual worker; all means for the development of production undergo a dialectical inversion so that they become means of domination and exploitation of the producers; they alienate from him the intellectual potentialities of the labour process in the same proportion as science is incorporated in it as an independent power...*

(Keynes, 1963) also discussed technologys potential for job destruction writing in the midst of the Great Depression that

> *We are being afflicted with a new disease of which some readers may not yet have heard the name, but of which they will hear a great deal*

> *in the years to come namely, technological unemployment. This means unemployment due to our discovery of means of economizing the use of labor outrunning the pace at which we can find new uses for labor.*

But Keynes goes on to say that this is only a temporary phase of maladjustment, predicting a future of leisure and plenty one hundred years hence. His contention that short-term pain permits long-term gain reinforced (Schumpeter, 1939) encomium to creative destruction.

In the fifties and sixties, with employment high and rapid real wage growth, Keynes and Schumpeters views held sway. Indeed, those raising concerns about technology were derided as Luddites.

Economic times have changed. Luddism is back in favor. (Autor et al., 2003), (Acemoglu and Autor, 2011), and (Autor and Dorn, 2013) trace recent declines in employment and wages of middle skilled workers to outsourcing by smart machines. (Katz and Margo, 2014) points to similar *labor polarization* during the early stages of Americas industrial revolution. (Goos et al., 2010) offer additional supporting evidence for Europe. However, (Schmitt et al., 2013) argue that 'robots' cant be 'blamed' for post-1970s U.S. job polarization given the observed timing of changes in relative wages and employment. A literature inspired by (Nelson and Phelps, 1966) hypothesizes that inequality may be driven by skilled workers more easily adapting to technological change, but generally predicts only transitory increases in inequality.

Our model supports some of the empirical findings and complements some of the theoretical frameworks in this literature. Its simple elements produce dynamic changes in labor market conditions, the nature and timing of which are highly sensitive to parameterization. But the model consistently features tech booms possibly followed by tech busts, evidence for which is provided in (Gordon, 2012) and (Brynjolfsson and McAfee, 2011).

A second prediction of our model is a decline, over time, in labors share of national income. U.S. national accounts record a stable percent share of national income going to labor during the 1980s and 1990s. But starting in the 2000's labors share has dropped significantly. (Frey and Osborne, 2017) try to quantify prospective human redundancy arguing that over 47 percent of current jobs will likely be automated in the next two decades. They also identify the priesthood, psychotherapy and coaching (parts of our service sector) as among the least subject to automation.

While our paper is about smart machines, its also about endogenous technological change. Schumpeter is clearly the father of this literature. But other classic contributions include (Arrow, 1962), (Lucas, 1988), (Romer, 1990), (Zeira, 1998), (Acemoglu, 1998), (Zuleta and Alberico, 2007), and (Peretto and Seater, 2013). Several of these papers endogenize technological change.

Our model accommodates long-run balanced growth arising from population- or labor-augmenting productivity growth.[4] But we abstract from these factors to focus on transitional growth arising from improvements in code retention.

Long term growth may be due to the cumulative impact steady state shifting technologies of this type.[5]

(Zeira, 1998) considered Leontief technologies and showed that countries with relatively high total factor productivity levels will adopt more capital-intensive techniques in producing intermediate inputs leading to cross-country dispersion in per capita income. But this adoption of new technology benefits workers since the two inputs are perfect complements in production.

(Zuleta and Alberico, 2007) considers an economy where the use of more capital-intensive technologies can be optimal, but doing so comes at a cost – a cost that goes beyond simply the price of hiring more capital. Like (Zeira, 1998), rich economies can get richer while poor economies, which can't afford the capital-intensification process, stagnate.

(Peretto and Seater, 2013) go considerably beyond (Zuleta and Alberico, 2007). They consider monopolistically competitive firms that invest in particular technologies depending on their relative costs. In their model, firms may specialize in the use of one technology or produce with multiple technologies. We investigate this issue here, but in a less robust manner.

Acemoglu also views technology as malleable. In (1998) he models technologies that can be altered to make particular skill groups, including labor, more productive. Hence, a temporary glut of one type of worker can initiate innovations culminating in higher productivity of such workers. It can also alter skill-formation decisions. (Acemoglu and Restrepo, 2016) endogenize the automation of labor as well as the invention of new labor-intensive products. The former (later) occurs to a greater (lessor) degree when wages are high.

(O'Rourke et al., 2013) examines 18th and 19th technological change in England with special focus on the skill premium. His model, which is similar to that of (Acemoglu, 1998), appears capable of matching the trend in the skill premium over the period.

Following (Acemoglu, 1998) and (Acemoglu and Restrepo, 2016), we model labor stocks of both types as exogenous. We make this simplification for three reasons. First, someone predisposed to provide services may not easily switch to producing code. Third, apart from the results on wage inequality, making all labor perfect substitutes doesn't alter our models' main conclusion. Third, if preferences and production are Cobb-Douglas the skill mix has no impact on the economy's equilibrium transition path.[6]

This literatures generally rather sanguine view of technology, namely as complementing human effort, differs from that presented here. Rather than technology permanently assisting humans, it ultimately largely replaces them. (Hemous and Olsen,) depart somewhat by calibrating a model in which capital can substitute for low-skilled labor while complementing high-skilled labor to explain technology-induced trends in the labor share of income and inequality.

2.2 A Modeling Framework for Understanding Economic Impacts of Robots

The first ingredient of any model of robot competition is, of course, one or more production processes that can produce particular goods or services with little or no input from humans. The second ingredient is one or more human-based production processes of specific goods and services that do not admit the easy substitution of non-human for human input. The third ingredient is dynamics, since technological change generally doesnt happen over night and since it takes time for new technologies to fully impact the economy. The fourth ingredient is agents that are differentially susceptible to replacement by robots. The fifth and final ingredient is a description of the manner in which robotic technology evolves. This includes the inclination and ability of humans to produce technology that puts themselves out of work.

The first ingredient permits production of particular goods to become less human dependent as robots become more abundant and capable. This process may involve the termination of particular human-intensive production processes. The second ingredient insures that humans have somewhere to go when they are put out of work or out of good work by robots. Taken together the first two ingredients help us consider a basic question surrounding robotic competition: Will the reduction in the cost of goods produced by more advanced robots compensate workers for the lower wages? The third ingredient dynamics is essential for determining how physical capital economic brawn is impacted through time by robot competition. After all, the counterpart of investment is saving and saving is done by households, not robots. The fourth ingredient, agents that are differentially outmoded by robots, is key for assessing the impact of robots on inequality. And the fifth ingredient, endogenous development of robots, is the driving force of interest.

Our model has each of these ingredients, but not all varieties of them. We dont, for example, include an alternative goods-production technology strictly utilizing labor and capital. Were we to do so, the economy would discretely switch, at some point, from non-robotic to robotic good production. Nor do we assume that goods production requires any direct human input. Adding this feature would not materially alter the qualitative nature of our findings. Similarly, we do not model code accumulation as contributing to TFP. That type of growth is well understood. Dynamics, the third ingredient, play a central role in our model and admit our central finding that better supply can, over time, mean worse demand. The fourth element different skill groups is covered by our inclusion of low-tech as well as high-tech workers. The presence of low-tech workers lets us consider whether technological change can flip the income distribution between people of different skill sets. Finally, our assumption that new software code is purchased provides a realistic means to endogenize development of robots.

2.3 Our Model

Agents consume the product of both sectors, goods and services. Goods, which can be consumed or invested, are produced using capital and code via a CES production function. The combination of capital and code that makes goods can be viewed as a smart machine or robot. Services, which are consumed when produced, are also created via CES production. New code is written by high-tech workers, and the stock of code is the sum of new and existing code. Old code requires maintenance, retention, and updating. This requirement is modeled as a form of depreciation. High and low-tech workers both live and consume for two periods, but work only when young.

Supply

Time t production of goods, Y_t, and services, S_t, follow (1) and (2),

$$Y_t = D_Y[\alpha(K_t)^{\frac{\varepsilon_y - 1}{\varepsilon_y}} + (1-\alpha)(A_t)^{\frac{\varepsilon_y - 1}{\varepsilon_y}}]^{\frac{\varepsilon_y}{\varepsilon_y - 1}}, \tag{2.1}$$

$$S_t = D_S[\gamma(H_{S,t})^{\frac{\varepsilon_s - 1}{\varepsilon_s}} + (1-\gamma)(G_t)^{\frac{\varepsilon_s - 1}{\varepsilon_s}}]^{\frac{\varepsilon_s}{\varepsilon_s - 1}}, \tag{2.2}$$

where $H_{S,t}$ is the amount of high-tech workers in the service sector, and G_t references low-tech workers. D_S and D_Y are total factor productivity terms, γ and α are CES parameters related to factor intensity, and ε_y and ε_s are CES elasticities. The stock of code A_t grows according to,

$$A_t = \delta A_{t-1} + zH_{A,t}, \tag{2.3}$$

where the depreciation factor is $\delta \in [0, 1)$. Higher δ means that legacy code is useful longer.[7] $H_{A,t}$ is the amount of high-tech labor hired by good firms, and z is the productivity of high-tech workers writing code.

The good sectors demands for code, high-tech workers, and capital satisfy[8]

$$\max_{K_t, A_t} Y_t(A_t, K_t) - m_t A_t - r_t K_t, \tag{2.4}$$

where the price of a unit of goods is one, m_t is the rental rate for code, and r_t is the interest rate. Factor demands for services reflect,

$$\max_{H_{S,t},G_t} q_t S_t(H_{S,t}, G_t) - w_t^G G_t - w_t^H H_{S,t}, \tag{2.5}$$

where q_t is the price of services, w_t^H is a high-tech worker's wage in the service sector, and w_t^G is a low-tech worker's wage.

Households save in the form of capital and code. Capital accumulation obeys

$$K_{t+1} = \phi I_t - p_t \delta A_t, \tag{2.6}$$

where I_t is the total resources of those born in t, ϕ is the saving propensity of the young, and $p_t \delta A_t$ is the value of code retained from the current period.

Factor prices satisfy

$$w_t^H = q_t D_S[\gamma(H_{S,t})^{\frac{\varepsilon_s - 1}{\varepsilon_s}} + (1-\gamma)(G_t)^{\frac{\varepsilon_s - 1}{\varepsilon_s}}]^{\frac{1}{\varepsilon_s - 1}}[\gamma(H_{S,t})^{-\frac{1}{\varepsilon_s}}], \tag{2.7}$$

$$w_t^G = q_t D_S[\gamma(H_{S,t})^{\frac{\varepsilon_s - 1}{\varepsilon_s}} + (1-\gamma)(G_t)^{\frac{\varepsilon_s - 1}{\varepsilon_s}}]^{\frac{1}{\varepsilon_s - 1}}[(1-\gamma)(G_t)^{-\frac{1}{\varepsilon_s}}], \tag{2.8}$$

$$r_t = D_Y[\alpha(K_t)^{\frac{\varepsilon_y - 1}{\varepsilon_y}} + (1-\alpha)(A_t)^{\frac{\varepsilon_y - 1}{\varepsilon_y}}]^{\frac{1}{\varepsilon_y - 1}}[\alpha(K_t)^{-\frac{1}{\varepsilon_y}}], \tag{2.9}$$

and

$$m_t = D_Y[\alpha(K_t)^{\frac{\varepsilon_y - 1}{\varepsilon_y}} + (1-\alpha)(A_t)^{\frac{\varepsilon_y - 1}{\varepsilon_y}}]^{\frac{1}{\varepsilon_y - 1}}[(1-\alpha)(A_t)^{-\frac{1}{\varepsilon_y}}]. \tag{2.10}$$

Households

Whether high-tech or low-tech, households maximize

$$u = (1-\phi)[(1-\kappa)log c_{y,t} + \kappa log s_{y,t}] + \phi[(1-\kappa)log c_{o,t+1} + \kappa log s_{o,t+1}], \tag{2.11}$$

where $c_{y,t}$, $c_{o,t}$, $s_{y,t}$, $s_{o,t}$, are consumption of goods and services by the young and old, respectively.[9]

Households maximize utility subject to,

$$c_{y,t} + q_t s_{y,t} + \frac{c_{o,t+1} + q_{t+1} s_{o,t+1}}{1 + r_{t+1}} = i_{j,t}, \tag{2.12}$$

where $i_{j,t}$ is total resources of group j. For low-tech workers,

$$i_{G,t} = w_t^G. \tag{2.13}$$

For high-tech workers laboring in the service sector,

$$i_{(H,S),t} = w_t^H, \tag{2.14}$$

and for high-tech workers writing code,

$$i_{(H,A),t} = z(m_t + \delta p_t), \tag{2.15}$$

where zm_t is revenue from renting out newly produced code and $z\delta p_t$ is revenue from the sale of the intellectual property. Note that like any asset price, p_t is a present value. The second component of the compensation of the code-writing high-tech workers reflect their sale of future rights to their newly written code or their retention and use of this code in their own firms.

High-tech workers are mobile between sectors. Assuming, as we do, no specialization, high-tech workers work in both sectors and receive the same total compensation regardless of where they work.

$$w_t^H = z(m_t + \delta p_t). \tag{2.16}$$

Household demands satisfy,

$$s_{y,t} = \frac{\kappa(1-\phi) i_{j,t}}{q_t}, \tag{2.17}$$

$$c_{y,t} = (1-\kappa)(1-\phi)i_{j,t}, \tag{2.18}$$

$$s_{o,t+1} = \frac{1+r_{t+1}}{q_{t+1}}[\kappa\phi i_{j,t}], \tag{2.19}$$

and

$$c_{o,t+1} = [1+r_{t+1}][(1-\kappa)\phi i_{j,t}]. \tag{2.20}$$

Equilibrium

Equilibrium requires

$$Y_t = C_{y,t} + C_{o,t} + K_{t+1} - K_t, \tag{2.21}$$

$$H_t = H_{A,t} + H_{S,t}, \tag{2.22}$$

and

$$S_t = S_{y,t} + S_{o,t}, \tag{2.23}$$

where C_y, C_o, S_y, S_o, are total consumption demand of goods and services by the young and old respectively.

Asset-market clearing entails equal investment returns on capital and code, i.e.,

$$p_t = \sum_{s=t}^{\infty} R_{s+1,t}^{-1}\delta^{s-t}m_{s+1}, \tag{2.24}$$

where $R_{s,t}$ is the compound interest factor between t and s, i.e.,

$$R_{s,t} = \prod_{j=t}^{s}(1+r_j). \tag{2.25}$$

The Model's Steady State

Despite the model's apparent simplicity, it yields no closed form expression for the steady-state capital stock.[10] However, a unique economically meaningful equilibrium exists in the general case.[11] For the Cobb-Douglas production case, the steady state is implicitly defined by the following two equations in $k = \frac{K}{A}$ and q.

$$\begin{aligned} D_y k^{\alpha} =& [\frac{(1-\phi)(1-\kappa)}{\phi}][k + \frac{(1-\alpha)D_y k^{\alpha}\delta}{1+\alpha D_y k^{\alpha-1}-\delta}] \\ &+ (1-\kappa)[k + \frac{(1-\alpha)D_y k^{\alpha}\delta}{1+\alpha D_y k^{\alpha-1}-\delta}][1+\alpha D_y k^{\alpha-1}] \end{aligned} \tag{2.26}$$

and

$$k + p\delta = \phi[z(m+p\delta)H + (1-\gamma)G(\frac{\gamma}{z(m+p\delta)})^{\frac{\gamma}{1-\gamma}}(qD_s)^{\frac{1}{1-\gamma}}], \tag{2.27}$$

where,

$$m = (1-\alpha)D_y k^{\alpha},$$

$$r = \alpha D_y k^{\alpha-1},$$

$$p = \frac{(1-\alpha)D_y k^{\alpha}}{1+\alpha D_y k^{\alpha-1}-\delta}.$$

Due to the model's analytic intractability, we proceed to a computational approach.[12]

Solving the Model

We calculate the economy's perfect foresight transition path following an immediate and permanent increase in the rate of code retention due, for example, to the development of the silicon chip. The solution is via Gauss-Seidel iteration (see (Auerbach and Kotlikoff, 1987)). First, we calculate the economy's initial and final steady states. This yields initial and final stocks of capital and code. These steady-state values provide, based on linear interpolation, our initial guesses for the time paths of the two input stocks. Next, we calculate associated guesses of the time paths of factor prices as well as the price paths of code and services. Step three uses these price paths and the models demand, asset arbitrage, and labor market conditions to derive new paths of the supplies of capital and code. The new paths are weighted with the old paths to form the iterations next guesses of capital and code paths. The convergence of this iteration, which occurs to a high degree of precision, implies market clearing in each period.

2.4 Simulating Transition Paths

The models main novelty is the inclusion of the stock of code in the production of goods. When the code retention rate, δ equals zero, good sector production is conventional based on contemporaneous amounts of capital and labor (code writers). But when δ rises, good production depends not just on capital and current labor, but, implicitly, on dead high-tech workers as well. We study the effects of this technological change by simulating an immediate and permanent increase in δ.

The increase in δ initially raises the compensation of code-writing high-tech workers. This draws more high-tech workers into code-writing, thereby raising high-tech worker compensation in both sectors. In most parameterizations, the concomitant reduction in service output raises the price of services. And, depending on the degree to which high-tech workers complement low-tech workers in producing services, the wages of low-tech workers will rise or fall.

Things change over time. As more durable code comes on line, the marginal productivity of code falls, making new code writers increasingly redundant. Eventually the demand for code-writing high-tech workers is limited to those needed to cover the depreciation of legacy code, i.e., to retain, maintain, and update legacy code. The remaining high-tech workers find themselves working in the service sector. The upshot is that high-tech workers can end up potentially earning far less than in the initial steady state.

What about low-tech workers?

The price of services peaks and then declines thanks to the return of high-tech workers to the sector. This puts downward pressure on low-tech workers' wages and, depending on the complementarity of the two inputs in producing services, low-tech workers may also see their wages fall. In this case, the boom-bust in high-tech workers' compensation generates a boom-bust in low-tech compensation. In the extreme, if high and low-tech workers are perfect substitutes, their wages move in lock step.

The economys dynamic reaction to the higher δ depends on the impact on capital formation. The initial rise in earnings of at least the high-tech workers can engender more aggregate saving and investment. The increased capital makes code and, thus, high-tech workers more productive. But if the compensation of high-tech and, potentially, low-tech workers falls, so too will the saving of the young and the economys supply of capital. Less capital means lower marginal productivity of code and higher interest rates. This puts additional downward pressure on new code rental rates as well as on the price of future rights to the use of code. A decrease in the depreciation rate of capital would necessarily have an opposite effect, as it raises capital stocks and the marginal product of code.

We next consider four possible transition paths, labeled Immiserizing Growth, Felicitous Growth, The First Will be Last, and Better Tasting Goods. Each simulation features an immediate and permanent rise in the code-retention rate. But the dynamic impact of this technological breakthrough can be good for some and bad for others depending on the size of the shock and other parameters. After presenting these cases, we examine the sensitivity of long-run outcomes to parameter assumptions.

Immiserating Growth

Figure 1 shows that a positive tech shock (the code-preservation rate, δ, rises from 0 to .7) can have negative long-term consequences. The simulation assumes Cobb-Douglas production of goods and linear production of services; i.e., both types of workers are perfect substitutes in producing services ($\varepsilon_S = \infty$).

As the top left panel indicates, national income quickly rises by 16 percent.[13] But it ultimately declines, ending up 13 percent below its initial steady-state value. Since preferences are logarithmic, expenditures on goods and services change by the same percentage. In the case of services, however, this occurs not only through changes in output levels, but also via changes in relative price.

The relative price of services first rises and then falls steeply, while service output does the opposite. Hence, in the long-run, both young and old agents end up consuming 28 percent less goods. And while their consumption of services is 27 percent larger, its not worth very much at the margin. In fact, its price is 32 percent lower than before the technological breakthrough.

Both types of workers earn the same under this parameterization. Their compensation initially jumps 11 percent and then starts to fall gradually. In the long run all workers end up earning 32 percent less than was originally the case.

What happens to the welfare of different agents through time? The initial elderly are essentially unaffected by the tech boom. The initial young experience a 14 percent rise in lifetime utility, measured as a compensating differential relative to their initial steady-state utility. But those born in the long run are 17 percent worse off.

The top right chart helps explain why good times presage bad times. The stock of code shoots up and stays high. But the stock of capital immediately starts falling. After six periods there is over 50 percent more code, but 65 percent less capital.

The huge long-run decline in the capital stock and associated rise in its marginal product (the interest rate) has two causes. First, as just stated, wages, which finance the acquisition of capital, are almost cut in half by the implicit competition with dead workers. Second, the advent of a new asset – durable code crowds out asset accumulation in the form of capital. When δ rises, all workers immediately enjoy an increase in their compensation. This leads to more saving, but not more saving in the form of capital. Instead, their extra saving as well as some of the saving they originally intended to do is used to acquire claims to legacy code. Initially, when the stock of code is small, its price is high. And, later, when the stock of code is large, its price falls to about 40 percent below its initial value. However, the total value of code increases enough to significantly crowd out investment in capital along the entire transition path.

Another way to understand capitals crowding out is to view legacy code, which coders can sell or retain when the code retention rate rises, as a form of future labor income. This higher resource permits more consumption of goods by low-tech workers (and high-tech workers, since they are paid the same) when the shock hits. And this additional good consumption means less goods are saved and invested. But the knock-on effect of having less capital in the economy is lower labor compensation. This reduces the consumption through time of workers, but also their saving.

What happens to labor's share of national income? Initially it rises slightly. But, in the long run, labor's share falls from 76 to 58 percent. This reflects the higher share of output paid to legacy code. The long-run decline in labors share of national income arises in all our simulations except those in which preferences shift toward the consumption of goods at the same time as the code retention rate rises.

Felicitous Growth

As figure 2 shows, the tech boom need not auger long-term misery. A higher saving preference is the key. In the immiserating growth case above, we assumed a youth saving propensity parameter, ϕ, of .2. This generated a ratio of consumption when young to consumption when old of 1.5 in the initial steady state and .9 in the long run steady state. Here we assume a ϕ of .95 while holding fixed the models other parameter values. The result is that good times can be good for good. But the road is rocky. Output ends up permanently higher, but only after an intervening depression. Output of both goods peaks in the period after the shock, with national income rising 41 percent. But in the long-run, it is only 18 percent higher – a major decline from its peak. The long-run expansion in output reflects less capital decumulation. In the prior simulation the capital stock immediately declined. Here the capital stock temporarily increases 14 percent above its initial value.

A less rapid decline in the capital stock and higher service prices boosts the common wage in the short term and leaves it at roughly its initial value in the long run. After peaking 47 percent above its initial value, the wage falls, ending up only 1 percent lower. The stock of code ends up more than twice as high. But the capital stock, notwithstanding the high rate of saving, declines by 35 percent.

The respective increase and decrease in the stocks of code and capital produce a significant rise in the economy's interest rate – 77 percent in the long run. Although the labor compensation of high and low-tech workers ends up very close to where it started, this increase in the interest rate permits those living in the future to consume significantly more.

Why does a high enough saving rate keep the δ shock from reducing long-run welfare? The answer is that whatever happens to the stock of code, a higher saving rate entails a higher capital stock and, therefore, higher labor compensation payments to high-tech workers. In the two above examples, we've considered widely varying saving preference parameters. Figure 7 shows how long-run utility varies with ϕ and δ.

The First Will Be Last

If high and low-tech workers are complements in producing services, their wage and utility paths will diverge. Consider, for example, the model with table 2's parameters shown in figure 3. As is always the case, the initial effect for high-tech worker of the δ shock is positive. Indeed, immediately after the shock hits, high-tech workers make 29 percent more than in the previous period. But low-tech workers, who, in this case, need high-tech workers to be productive, see their wages fall one percent as the share of high-tech workers working in services immediately falls from 50 percent to 38 percent.

However, as code accumulates and capital decumulates, high-tech workers start earning less in code-writing and move in great number back to the service sector. Ultimately, 68 percent of high-tech workers work in the service sector. And their return to that sector drives down their wage compared both its initial value and to the long-run wage of low-tech workers. Indeed, in the final steady state, high-tech workers earn 14 percent less than in the initial steady state. Low-tech workers, in contrast, earn 17 percent more. But, interestingly, in period 3 their wage peaks 26 percent above its original value. This rise and fall in the wages of low-tech workers reflects, in part, the rise and fall in the price of services.

Better Tasting Goods

Our assumption above that the share of each type of good in consumption is fixed is an important one. It is reasonable given that there is no strong evidence about whether technological innovations are shifting consumption towards or away from goods that are relatively labor intensive. In this section we reinterpret the utility function of equation 11 as a technology for Cobb-Douglas production of a final consumption good using a combination of goods and services. [14] Figure 4 displays the consequences of having κ fall from .5 to .25 at the same time δ rises. Other parameters are those in the 'First Will Be Last' case.

This additional shock has a dramatic impact on the path of national income. When the shock hits national income increases 7 percent. In the long run it drops 4 percent.

What explains this result? Shouldnt a shift in production functions towards products that have become easier to produce be economically beneficial? As in previous cases, immiseration is caused by capital decumulation. Capital stocks in this case decrease 40 percent in the period after the shock, and 84 percent in the long-run. Capital decumulation is exacerbated by the κ shock in three ways. First, increased immediate consumption demand for goods (i.e., reduced demand for services) increases the share of high-tech workers working as coders. This translates, after one period, into more legacy code and lower labor compensation, the source of saving and capital formation. Second, the increase in immediate good consumption reduces the amount of capital available to invest. Third, the shift in demand toward goods limits the rise in the price of services. This, too, has a negative impact on wages and capital formation.

The Large Range of Potential Outcomes

As just demonstrated, the models reaction to the δ shock is highly sensitive to parameter values. We now consider this sensitivity in more detail. Figure 5 jointly displays our previous results. Table 3 shows additional results for several different parameter combinations. The tables baseline simulation (row one) assumes intermediate parameter values. Subsequent rows show the impact of sequentially modifying one parameter. Figure 6 plots the path of national income for each row of the table.

These simulations teach several new things. First, high-tech workers benefit from substitutability in the goods sector. In the perfect substitutability case the productivity of high-tech workers is independent of supplies of code and capital.

Second, with both Cobb-Douglas production and preferences, the path of the capital-to-code ratio in response to a rise in delta, staring from $\delta = 0$, is independent of the absolute and relative numbers of each type of worker.[15]

Third, a positive δ shock always produces a tech boom with increases in both the price of code and the wage of high-tech workers.[16] In most simulations, the boom is short lived, auguring a major tech and saving bust. Fourth, in most simulations capital becomes relatively scarce compared to code leading to a rise in interest rates. Finally, the δ shock generally raises labor share in the short run and lowers it in the long run.

Figure 7 presents a contour graph of the long-run compensating differential. Its top half considers combinations of saving preference parameters ϕ and shocks to δ assuming table 1s values of the other parameters. Because the two types of workers are perfect substitutes, the compensating differential for them is the same. Redder areas denote higher long-run utilities relative to the initial steady state. Bluer areas denote the opposite. Long-run utility increases most when δ is large and the saving rate is high. It decreases the most when the δ shock is high and the saving rate is low.

Figure 7s bottom half considers joint shocks to the saving rate and code-writing productivity (z). Higher values of each reinforces their individual positive impacts on long-run utility. As opposed to δ shocks, shocks to code-writing productivity (z)

enhance all agents welfare. The reason is simple this shock makes living, but not dead high-tech workers more productive. Increasing labor's productivity in other tasks has the same result. As this model has no disutility from labor, reducing labor's productivity is isomorphic to restricting its supply. Policies that attempt to raise wages by reducing labor supply - such as increasing the minimum wage - will therefore backfire.

Figure 8 considers combinations of the saving rate, ϕ, and the good sectors elasticity of substitution, ε_y. It shows the aforementioned sensitivity of long-run utility to the substitutability of code for capital. It also indicates that this sensitivity is greater for low than for high saving rates. Higher substitutability moderates the negative effects of capitals crowding out that occurs with low savings.

2.5 The Role of Property Rights and Rivalry

To this point we've assumed that code is private and rival. Specifically, we've assumed that when one firm uses code it is unavailable for rent or use by other firms. But unlike physical capital, code represents stored information that may be non-rival in its use. Non-rivalry does not however necessarily imply non-excludability. Patents, copyrights, trade secrets, and other means can be used to limit code's unlicensed distribution. On the other hand, the government can turn code into a public good by mandating it be open source.

This section explores two new scenarios. The first is that code is non rival and non excludable in its use, i.e., it is a public good. The second is that code is non rival, but excludable. To accommodate these possibilities we modify our model in two ways. We assume that each firm faces a fixed cost of entry. And we assume that each firm is endowed with a limited supply of public code. These assumptions ensure a finite number of firms operating with non-trivial quantities of capital. To compare these two new settings with what came above the case of private (rival and excludable) code, we rewrite our baseline model with the two new assumptions.

Rival, Excludable (Private) Code

With a fixed public code endowment and fixed entry costs, profit maximization satisfies:

$$\pi_{j,t} = F(k_{j,t}, zH_{j,t} + a_{j,t} + \overline{A}) - C - r_t k_{j,t} - m_t a_{j,t}, \tag{2.28}$$

where $\pi_{j,t}$ are profits for firm j at time t, $F(\bullet)$ is the same CES production function as in the baseline model, $k_{j,t}$ is the amount of capital rented by the firm, $a_{j,t}$ is the amount of code rented by the firm, $H_{j,t}$ is the amount of high-tech labor hired by the firm, $\overline{A}$ is the exogenously set amount of free code in the economy, and C is the cost of creating a new firm. This cost must be paid each period. In equilibrium all firms have zero profits.

$$0 = F(k_{j,t}, zH_{j,t} + a_{j,t} + \overline{A}) - C - r_t k_t - m_t a_{j,t}. \tag{2.29}$$

Market clearing conditions are,

$$\sum a_{j,t} = \delta A_{t-1}, \tag{2.30}$$

$$\sum k_{j,t} = K_t, \tag{2.31}$$

$$\sum H_{j,t} = H_{A,t}, \tag{2.32}$$

$$Y = c_{o,t} + c_{y,t} - K_t + K_{t+1} + NC, \tag{2.33}$$

where N is the number of firms. Since all firms are identical, (26) provides an expression for N, the number of firms.

$$0 = NF(\frac{K_t}{N}, zH_t + \frac{1}{N}\delta A_{t-1} + \overline{A}) - NC - r_t K_t - m_t \delta A_{t-1} \tag{2.34}$$

Firms enter up to the point that the value of the public code they obtain for free, namely $\overline{A}$, equals their fixed cost of production. Thus,

$$\overline{A}F_{a,t} = C. \tag{2.35}$$

This fixes the marginal product of code at $\frac{C}{\overline{A}}$ in every period. Intuitively, new firms can acquire a perfect substitute for new code, and, thus, new coders at a fixed cost by setting up shop and gaining access to $\overline{A}$ in free code. Given that good production obeys constant returns to scale, fixing codes marginal product means fixing the ratio of capital to code. This, in turn, fixes the interest rate. Hence, the rental rates of coders and capital are invariant to the increase in δ.

Although the increase in δ doesnt raise the current productivity of coders, it does raise the present value of their labor compensation. The reason is that coders can now sell property rights to the future use of their invention. Hence, unlike our initial model, this variant with fixed costs and a free endowment of code does not admit immiserating growth absent some additional assumptions.[17]

Were the number of firms to remain fixed, the jump in δ would entail more code per firm with no higher capital per firm. This would mean a lower marginal productivity of code, which (35) precludes. It would also mean a negative payoff to setting up a new firm. Hence, the number of firms must shrink in order to raise the level of capital per firm as needed to satisfy (35).

To solve the model an additional step is added to the iteration procedure. Given a guess of prices and stocks in a period, (34) is used to calculate N. This guess of N in each period is included in the next iteration to calculate new prices.[18]

Figure 9 shows transition paths for key variables for this excludable, non-rival model based on Table 4's parameter values. Note that high-tech workers earn 14 percent more in the long run and enjoy commensurately higher utility. Low-tech workers are also better off. There is also a modest increase in the economy's capital stock.

Non-Rival, Non-Excludable (Public) Code

Consider next the case that code, in the period after it is produced, is a pure public good used simultaneously by every firm. This possibility could arise by government edict, the wholesale pirating of code, or reverse engineering.

Profits are now

$$\pi_{j,t} = F(k_{j,t}, zH_{j,t} + a_{j,t} + \overline{A}) - C - r_t k_{j,t}, \tag{2.36}$$

as firms no longer need to rent their stock of code ($a_{j,t}$), where

$$a_{j,t} = \delta A_{t-1} \forall j \tag{2.37}$$

As before, firm entry and exit imply zero profits,

$$0 = NF(\frac{K_t}{N}, zH_t + \delta A_{t-1} + \overline{A}) - NC - r_t K_t. \tag{2.38}$$

and

$$(\delta A_{t-1} + \overline{A}) F_{a,t} = C. \tag{2.39}$$

Finally, with investment in code no longer crowding out investment in capital,

$$K_{t+1} = \phi I_t. \tag{2.40}$$

Figure 10 shows results for this case again with Table 4s parameter values. The initial steady state is the same as in the prior case of excludable rival code. However, the response to the jump in δ are dramatically different. The jump in δ has no immediate impact on the economy because high-tech workers no longer hold copyright to their code.

In the period after the shock, the economy begins to react. The stock of free public code, which now includes both $\overline{A}$ plus all of the economys legacy code, is larger. This induces more firm entry. Indeed, the number of firms more than doubles. As indicated in equation 39, with more free code available, new entrants can cover the fixed costs of entry with a lower value per unit of free code, i.e., with a lower marginal product of code. The lower marginal product of code and, thus, of coders leads to an exodus of high-tech workers from coding into services. In the long run, the number of high-tech workers hired for their coding skills falls by 30 percent and their wage falls by 25 percent. National income peaks at 5 percent above its initial level in this period. The interest rate rises by 35 percent and the wage of low-tech workers decreases by 10 percent.

The economy's transition is characterized by a series of damped oscillations as periods of relatively high coder hiring is followed by periods of plentiful free code and relatively low coder hiring. Most importantly, the long-run impact of this change is a net immiseration with long-run national income 8 percent below its initial steady state level.

As in the baseline model, the main mechanism for immiseration is the reduction of the high-tech wage leading to lower capital accumulation. A secondary reason is the inefficiency introduced due to high-tech workers no longer being able to internalize the full value of their creation of new code.

Non-Rival, Excludable (Private) Code

A third possibility is that code is excludable, but non-rival in its use, permitting high-tech workers to license all their code to all firms. The equations for the rival, excludable model hold with the following exceptions. First, profits are given by

$$\pi_{j,t} = F(k_{j,t}, zH_{j,t} + \delta A_{t-1} + \overline{A}) - C - r_t k_{j,t} - m_t \delta A_{t-1} \tag{2.41}$$

Second, the price of code reflects its use by all firms.

$$p_t = \sum_{s=t}^{\infty} R^{-1}_{s+1,t} \delta^{s-t} m_{s+1} N_{s+1}. \tag{2.42}$$

As shown in figure 11, the δ shock produces a felicitous transition path, indeed far better than the rival excludable case. As in the rival, excludable case, firms entry satisfies equation 35. Hence, the marginal product of new code is fixed. So is the marginal product of capital, i.e., the interest rate.

2.6 Endogenous Production Technology

So far weve assumed a single means of producing goods. Here we permit good producers to switch between more and less code-intensive production techniques. To keep matters simple we assume the good sector's production function is Cobb-Douglas and that good producers can choose the parameter on A (and thus on K) such that $\alpha \in [\alpha_1, \alpha_2]$. In the initial steady state, $\alpha_1 = \alpha_2$, but when δ is shocked, the range of possible technologies is expanded as well.

This is simulated via an additional step in the iteration process. After a guess of the path of code and capital is made, an $\alpha \in [\alpha_1, \alpha_2]$ is selected in every period to maximize good output. Subsequently, prices are calculated from marginal products and a new guess of the path of inputs is made.

Given the inputs, and the prevailing stocks of code and capital, output is convex in α. Hence, firms will produce using either the lowest or highest value.[19] This results in the economy flipping back and forth repeatedly, although not necessarily every period, from the most to the least capital-intensive technology. Since our solution method relies on the economy reaching a stable steady state, we set α to a fixed value, namely α_2, far enough in the future such that the transition path for the initial several hundred periods is unaffected.

Figure 12 presents results based on table 5s parameter values. Unlike the previous figures, the absolute amounts of capital and code stocks reflect the dependency of the choice of technology on the ratio of the two stocks. In the initial steady state, the code stock consists just of newly produced code and, naturally, is low. The economy is in a capital-intensive steady state. After the δ shock, code begins to accumulate. In the fourth period, sufficient code is accumulated to lead producers to switch technologies toward more code-intensive production. But the switch to code-intensive production raises wages and, thus, workers saving. Due to our assumed high saving preference ($\phi = .9$), the increase in saving more than offsets the increase in the value of claims to code and the capital stock increases. If the saving preference were lower, capital stocks would not rise, and the economy would remain permanently in a code-intensive equilibrium. In this case, however, the increase in saving is large enough to drive producers to adopt a capital-intensive technology in the next period. This leads to lower wages, which, over time, means a lower capital-code ratio and a subsequent switch back to code-intensive production.

This ongoing cycle has important welfare implications. High-tech workers who are young when the code-intensive technology is used will earn a high wage when young and high interest rates when old. Those unfortunate enough to be young in a period when a high alpha is chosen will earn low wages while young and low interest rates when old.

Because a period in our model corresponds to roughly 30 years, this cycle of technologically driven booms and busts bears a striking resemblance to the 'long-wave' theories of early economists such as Schumpeter and Kondratieff. While evidence for the existence of such cycles is limited ((Mansfield, 1983)), this model's long-wave cycles reflect a different mechanism from those in (Rosenberg and Frischtak, 1983).

2.7 Testable Implications and Supportive Evidence

Each of our models simulations feature a temporary rise followed by a decline in labors share of national income as well as a rise in code as a share of total assets. U.S. labor-share data going back four decades provides support for these trends.[20] There is also recent evidence of a decline in capital per worker, consistent with our models immiseration scenarios.

Figure 2·15 displays three measures of labors share of U.S. income based on three approaches to handing labors unknown share of proprietorship and partnership income. The orange and gray curves use Bureau of Economic Analysis (BEA) data. The orange curve charts labors share of the sum of all non-proprietorship income.[21] This is our equal share measure because it effectively assumes that labor's share of proprietorship income is the same as that of national income. The blue curve displays labor's share of corporate income, i.e., it simply ignores the non-corporate sector.

The yellow curve displays labors share of all private businesses output including proprietorships as calculated by the Bureau of Labor Statistics (BLS). The BLS imputes labors share in proprietorship income by assuming proprietors and partners annual labor income equals the annual average wage earning in their industry. Any proprietor income above this amount is considered capital income. This measure is smaller than the others because the BLSs income measure is not net of depreciation.

By all three measures, labors share of income is lower in 2015 than in the mid 1970s. In the yellow curve, labors share peaks in the mid-1970s with the two lowest shares recorded in 2014 and 2015.

The precise percentage-point decline in labor's share between 1975 and 2014 are 5.96 percentage points, 5.88 percentage points, or 4.88 percentage points according to the orange, gray, and yellow curves, respectively.

Other authors, including (Karabarbounis and Neiman, 2014) and (Bridgman et al., 2014), report similar findings using related labor-share measures. The consensus view is that labors share has decreased significantly since peaking in the mid 1970s.

(Armenter, 2015) considers the possibility that the decrease in the BLS's measure is driven by the assumption that the proprietors pay themselves the average wage in an industry. When he instead fixes labors share of proprietors income at 85 percent, labor share since 1975 still falls, but by less.

Code stocks have certainly increased since the invention of the digital computer and the silicon chip. Figure 2·16 reports stocks of R&D and software as a share of total US fixed assets. According to the BEA, software grew from almost 0 percent of capital in 1960 to over 1.5 percent today. Combined software and R&D stocks have grown as a share of capital by about 3.5 percentage points over the same period. [22]

Many papers suggest that the BEA underestimates the stock of organizational capital and code complementary to computers. (Brynjolfsson et al., 2002) find that firms with large investments in computer capital have much higher valuations, that computer capital investments lead to disproportionately large increases in firm valuations, and that firms that make such investments tend to be more productive in future years. Similarly, (Hulten and Hao, 2008) find that the book value of R&D-intensive firms in 2006 explains only 31 percent of their valuation. Both these papers argue that only firms who have made large investments in organizational and technological capital are able to implement innovative technologies.

Code and software controlled by firms that arent counted as assets by the BEA still increase the productivity of firms. Such firms would be more valuable than they should be based on only their observed assets. Figure 2·17 shows the value of the US corporate sector less the replacement cost of its physical and financial assets.[23] This measure of the stock of intangible assets is highly cyclical because due to the volatility of the stock market. Despite this, it shows a clear secular increase starting in the mid 1970s. For firms in the S&P 500, intangible assets increased from 17 percent of market value in 1975 to 84 percent in 2015 ((Ocean Tomo LLC, 2015)).

Hall (2001) argues that the increase in the value of economy-wide intangible assets, and therefore Tobins (average) q, is due to the creation of code and organizational capital within firms, which he calls e-capital. (Barkai, 2016) also notes that firms output per unit of observed capital has increased even as the marginal cost of capital (as measured by the real interest rate) has decreased dramatically. Assuming that capital's average product is equal to its marginal product, he interprets this trend as being due to an increase in market power and markups. [24]

Long-run immiseration in our model hinges on a long-run decline in capital per worker. While capital per worker increased at an average rate of 2.5 percent from 1985 to the present, the years 2011 through 2015 have seen a decrease in capital per worker of .5 percent per year on average. This is the longest and most dramatic decrease on record.[25] Further, this measure significantly underestimates the extent to which physical capital per person has decreased. Capital services as measured by the BLS include accumulation of intellectual property and capital quality increases (through the deflator) that are attributable in our model not to physical capital per worker but to larger stocks of code.

2.8 Conclusion

Will smart machines, which are rapidly replacing workers in a wide range of jobs, produce economic misery or prosperity? Our two-period, OLG model admits both outcomes. But it does firmly predict three things - a long-run decline in labor share of income (which appears underway in OECD members), tech-booms followed by tech-busts, and a growing dependency of current output on past software investment.

The obvious policy for producing a win-win from higher code retention is taxing those workers who benefit from this technological breakthrough and saving the proceeds. This will keep the capital stock from falling and provide a fund to pay workers a basic stipend as their wages decline through time. Other policies for managing the rise of smart machines may backfire. For example, restricting labor supply may reduce total labor income. While this may temporarily raise wages, it will also reduce investment and the long-term capital formation on which long-term wages strongly depend. Another example is mandating that all code be open source. This policy removes one mechanism by which capital is crowded out, but it leads firms to free ride on public code rather than hire new coders. This reduces wages, saving, and, in time, the capital stock.

Our simple model illustrates the range of things that smart machines can do for us and to us. Its central message is disturbing. Absent appropriate fiscal policy that redistributes from winners to losers, smart machines can mean long-term misery for all.

2.9 Annex: Tables and Charts

Table 2.1: Parameters for Immiserating Growth

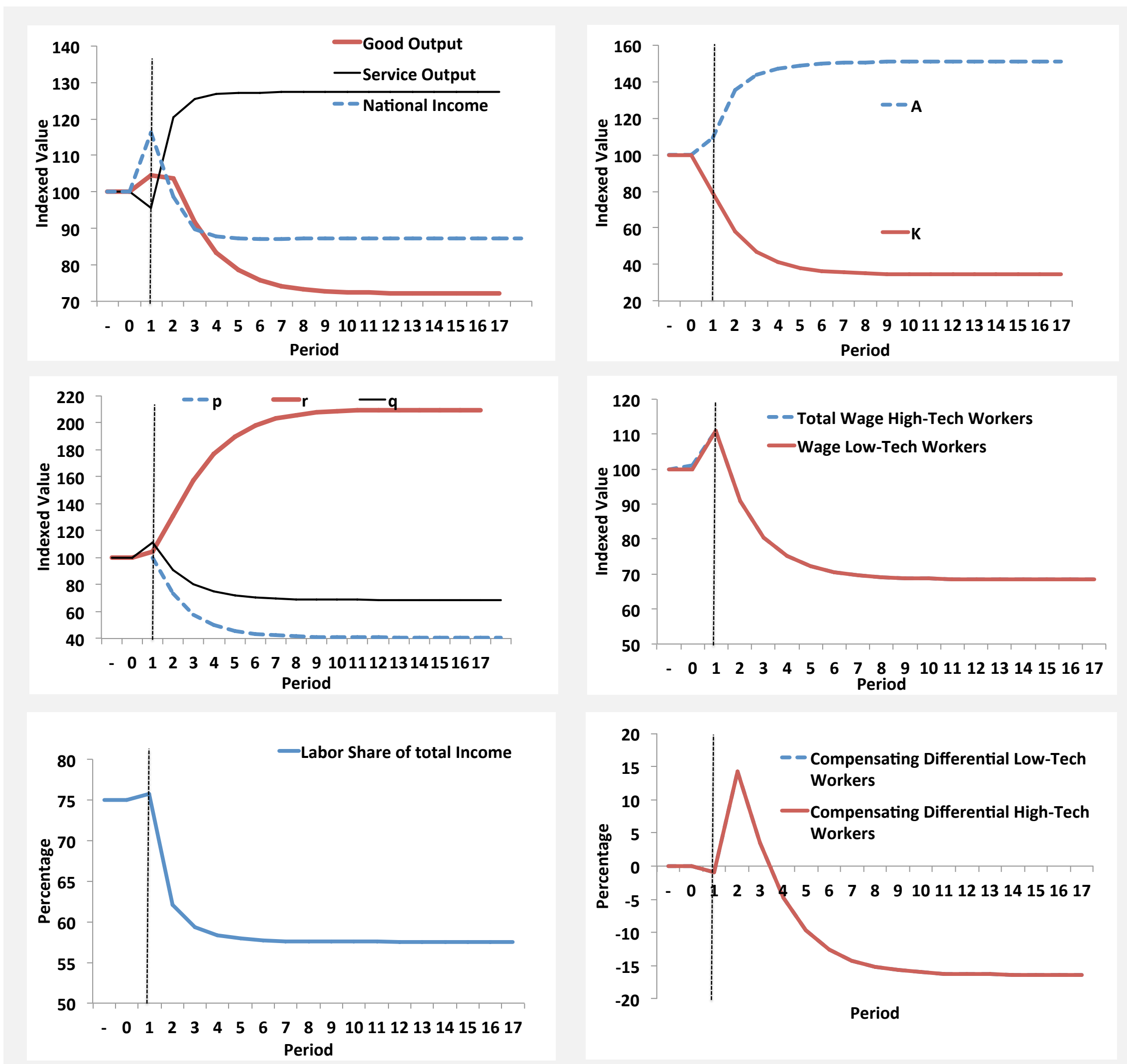
Model Parameter	Role	Value
ε_s	Elasticity in Service Sector	∞
ε_y	Elasticity in Good Sector	1
γ	Service High-Tech Input Share Param.	0.5
α	Good Capital Input Share Param.	0.5
δ	Code Retention Rate	0 shocked to 0.7
ϕ	Saving Preference Param.	0.2
H	High-Tech Worker Quantity	1
G	Low-Tech Worker Quantity	1
κ	Service Consumption Share	0.5
z	Code Writing Productivity	1
D_y	TFP in Goods	1
D_s	TFP in Services	1

Note: This table gives parameter values for the first illustration of the effects of a one-time, permanent increase in the depreciation rate, δ, from zero to .7. We take the intermediate value of .5 for κ, α, and γ. The productivity terms z, D_Y, and D_S, are set to one. In this and all subsequent simulations invoking an elasticity of 1 (except for the endogenous technology extension) the true elasticity is actually 1.0001.

Table 2.2: Parameters for The First Will Be Last

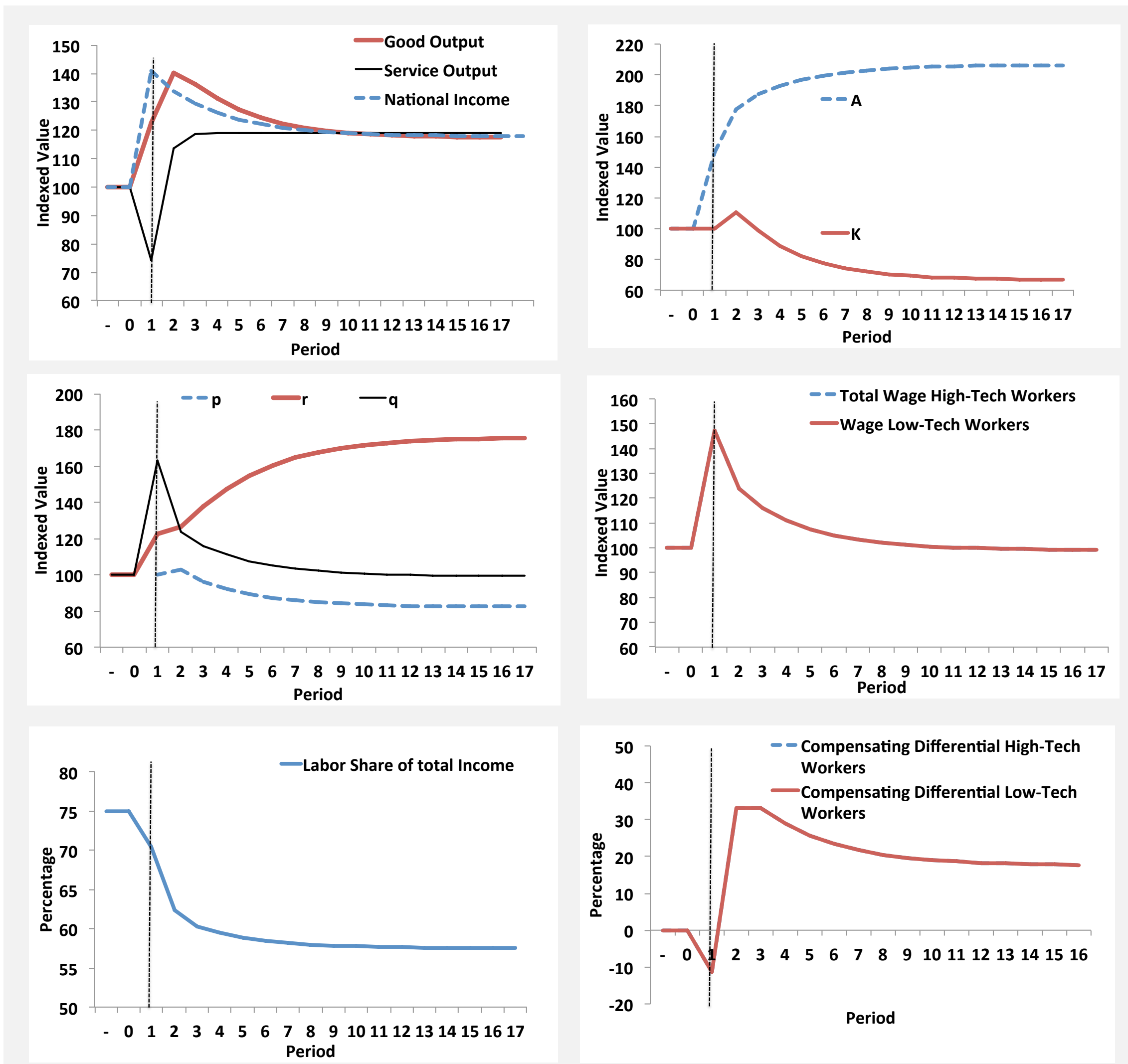
Model Parameter	Role	Value
ε_s	Elasticity in Service Sector	1
ε_y	Elasticity in Good Sector	1
γ	Service High-Tech Input Share Param.	0.5
α	Good Capital Input Share Param.	0.5
δ	Code-Retention Rate	0 shocked to 0.7
ϕ	Saving Preference Parameter	0.7
H	High-Tech Worker Quantity	2
G	Low-Tech Worker Quantity	1
κ	Service Consumption Share	0.5
z	Code Writing Productivity	1
D_y	TFP in Goods	1
D_s	TFP in Services	1

Figure 2·1: Immiserating Growth



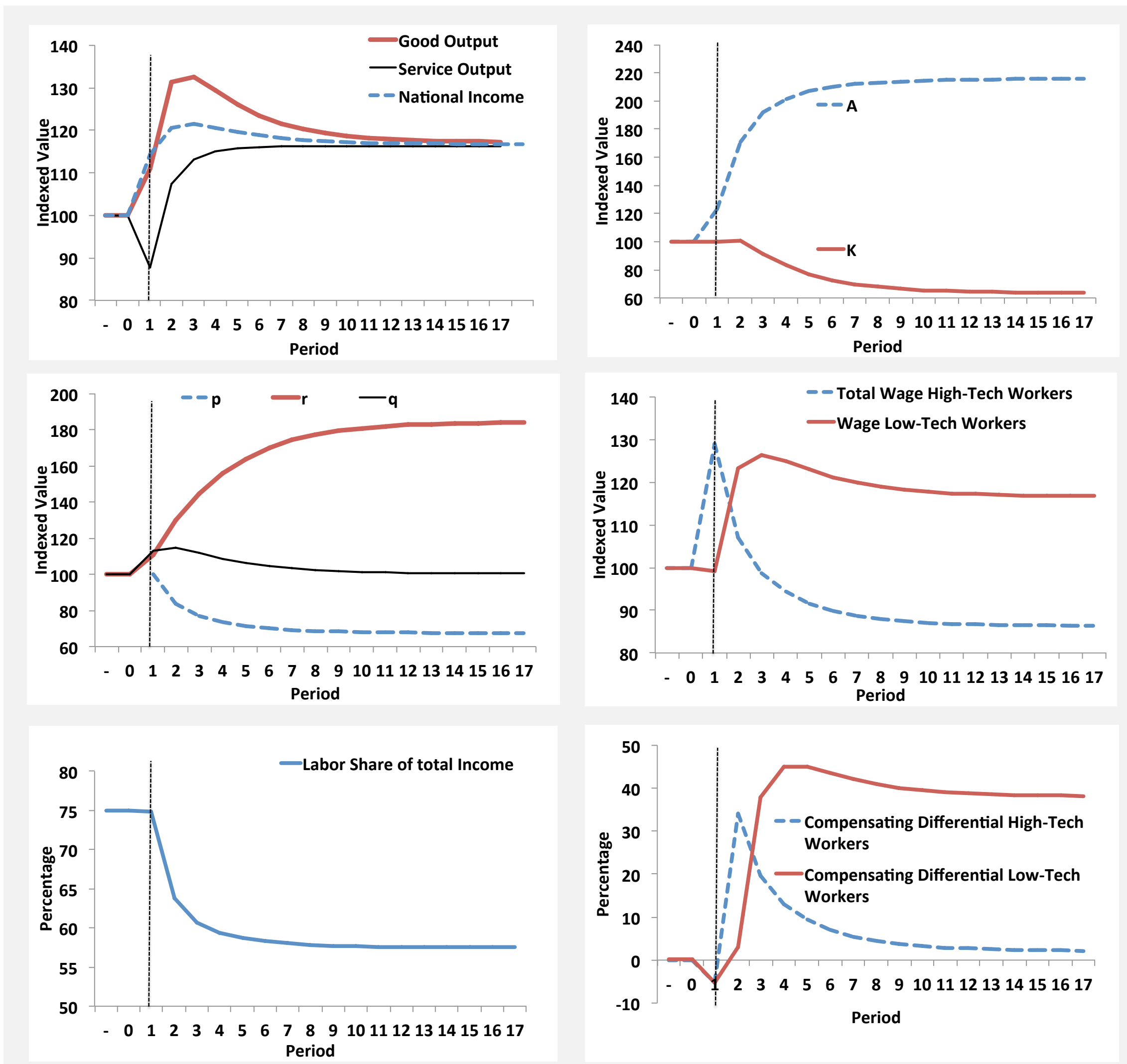
Note: Transition paths based on Table 1. "Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective transition utility levels. Service and goods output are raw indexed output, not market value. Period 1 non-indexed prices in units of the good are $r = 1.737$, $q = .349$, and $p = .043$.

Figure 2·2: Felicitous Growth



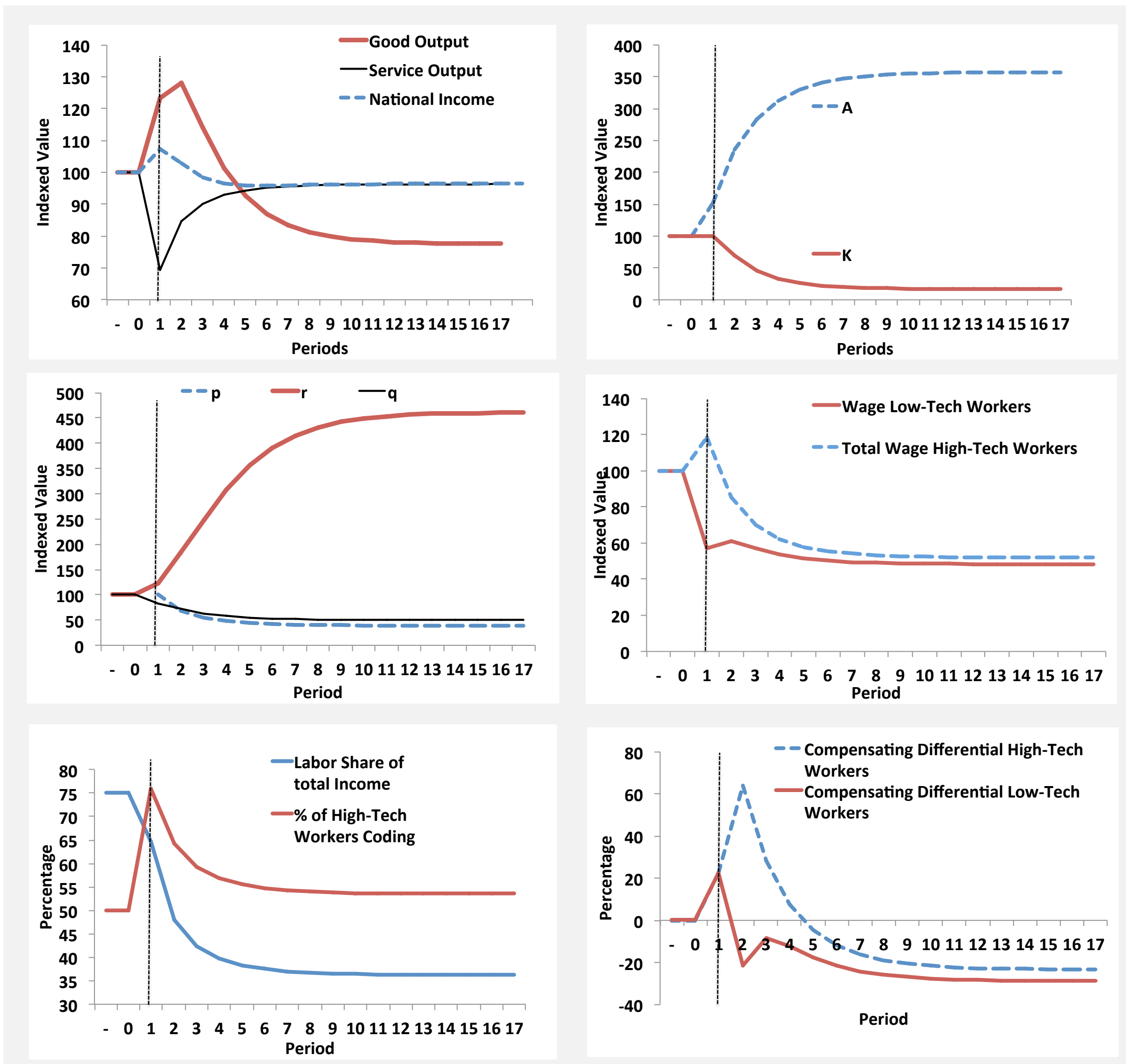
Note: Transition paths based on Table 1, with the exception of a higher saving rate ($\phi = .95$). "Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective transition utility levels. Service and goods output are raw indexed output, not market value. . Period 1 non-indexed prices in units of the good are $r = .454$, $q = 2.204$, and $p = .631$.

Figure 2·3: The First Shall Be Last



Note: Transition paths based on Table 2. "Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective transition utility levels. Service and goods output are raw indexed output, not market value. Period 1 non-indexed prices in units of the good are $r = .529$, $q = 1.317$, and $p = .398$.

Figure 2·4: Better Tasting Goods



Note: Transition paths based on Table 2, except in addition to the δ shock, κ is simultaneously shocked from .5 to .25. "Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective transition utility levels. Service and goods output are raw indexed output, not market value. Period 1 non-indexed prices in units of the good are $r = .587$, $q = .784$, and $p = .200$.

Table 2.3: Parameters for Institutional Simulations

Model Parameter	Role	Value
ε_s	Elasticity in Service Sector	1
ε_y	Elasticity in Good Sector	1
γ	Service High-Tech Input Share Param.	0.5
α	Good Capital Input Share Param.	0.5
δ	Code Retention Rate	0 shocked to 0.25
ϕ	Saving Rate	0.5
H	High-Tech Worker Quantity	1
G	Low-Tech Worker Quantity	1
κ	Service Consumption Share	0.5
z	Code Writing Productivity	1
D_y	TFP in Good Sector	1
D_s	TFP in Service Sector	1
C	Firm Setup cost	.055
$\overline{A}$	Exogenous Free Code	.25

Note: This table gives parameter values for illustrations of the effects of a one-time, permanent increase in the depreciation rate, δ, from zero to .25 given different institutional settings.

Table 2.4: Parameters for the Endogenous Technology Extension

Model Parameter	Role	Value
γ	Service High-Tech Input Share Param.	0.5
α	Good Capital Input Share Param.	[0.3, 0.5]
δ	Code-Retention Rate	0 shocked to 0.6
ϕ	Saving Rate	0.9
H	High-Tech Worker Quantity	1
G	Low-Tech Worker Quantity	10
κ	Service Consumption Share	0.5
z	Code Writing Productivity	1
D_y	TFP in Goods	1
D_s	TFP in Services	1

Baseline

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	1.0	1.0	**0.0**	0.5	1.0	1.0	0.5	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	50.0	100.0	75.0	50.0	0.0	-49.9
1	1.0	1.0	**0.5**	0.5	1.0	1.0	0.5	0.5	1.0	113	117.5	106.4	100.0	112.6	100.0	108.4	106.1	50.7	115.9	66.8	56.3	20.3	-47.4
2	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	110	116.0	109.1	96.6	143.0	89.7	108.5	121.7	57.7	101.9	65.6	43.4	8.9	-38.3
3	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	109	113.2	109.6	88.3	152.4	85.7	105.7	131.4	57.6	96.8	65.6	40.5	4.5	-37.7
4	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	109	111.0	109.7	82.1	156.0	83.6	103.3	137.8	56.7	94.2	64.8	39.9	2.3	-38.5
10	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	108	107.0	109.6	71.9	159.8	80.5	99.0	149.1	54.3	90.4	62.7	40.0	-1.0	-40.5
Steady State	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	108	106.7	109.5	71.1	160.0	80.2	98.7	150.0	54.1	90.1	62.5	40.0	-1.2	-40.7

Spirituality Taste Shock κ Jumps from 0.5 to 0.75

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	1.0	1.0	0.0	0.5	1.0	1.0	**0.5**	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	50.0	100.0	75.0	50.0	0.0	-49.8
1	1.0	1.0	0.5	0.5	1.0	1.0	**0.75**	0.5	1.0	153	117.2	120.6	100.0	87.1	100.0	135.0	93.4	71.8	127.1	58.4	43.6	20.3	-47.3
2	1.0	1.0	0.5	0.5	1.0	1.0	**0.75**	0.5	1.0	146	129.2	123.6	140.0	98.2	97.7	145.5	83.7	87.8	120.7	67.2	27.3	8.9	-38.2
3	1.0	1.0	0.5	0.5	1.0	1.0	**0.75**	0.5	1.0	143	136.7	124.4	173.0	96.4	99.0	150.9	74.7	93.2	122.1	72.0	23.7	4.5	-37.6
4	1.0	1.0	0.5	0.5	1.0	1.0	**0.75**	0.5	1.0	141	142.0	124.8	200.0	93.4	100.2	154.4	68.4	96.0	124.1	74.6	22.6	2.3	-38.4
10	1.0	1.0	0.5	0.5	1.0	1.0	**0.75**	0.5	1.0	137	154.1	125.6	275.8	85.2	102.8	161.6	55.6	101.5	128.6	80.2	21.2	-1.0	-40.4
Steady State	1.0	1.0	0.5	0.5	1.0	1.0	**0.75**	0.5	1.0	137	156.5	125.8	293.4	83.5	103.2	162.7	53.4	102.3	129.4	81.3	20.9	-1.2	-40.6

Corn Taste Shock κ Jumps from 0.5 to 0.25

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	Coders Corn Sector	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	1.0	1.0	0.0	0.5	1.0	1.0	**0.5**	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	50.0	100.0	75.0	50.0	0.0	-49.9
1	1.0	1.0	0.5	0.5	1.0	1.0	**0.25**	0.5	1.0	76	117.2	81.6	100.0	149.3	100.0	66.9	122.2	23.8	94.0	70.5	74.7	22.3	-68.9
2	1.0	1.0	0.5	0.5	1.0	1.0	**0.25**	0.5	1.0	69	102.4	84.1	66.0	208.1	71.5	55.7	177.6	22.7	68.3	56.4	66.8	-4.5	-68.2
3	1.0	1.0	0.5	0.5	1.0	1.0	**0.25**	0.5	1.0	65	91.9	84.8	44.9	233.3	58.1	46.9	227.9	19.7	55.8	52.3	64.6	-18.2	-71.0
4	1.0	1.0	0.5	0.5	1.0	1.0	**0.25**	0.5	1.0	62	85.4	85.0	34.4	244.7	51.2	41.7	266.5	17.7	49.1	49.0	64.1	-25.7	-73.2
10	1.0	1.0	0.5	0.5	1.0	1.0	**0.25**	0.5	1.0	59	76.7	84.9	23.1	255.6	42.9	34.8	332.7	14.8	41.0	44.0	64.0	-34.9	-76.5
Steady State	1.0	1.0	0.5	0.5	1.0	1.0	**0.25**	0.5	1.0	59	76.3	84.9	22.7	255.9	42.6	34.6	335.6	14.7	40.7	43.8	64.0	-35.2	-76.6

Low Saving Rate ϕ = 0.1

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	1.0	1.0	0.0	**0.1**	1.0	1.0	0.5	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	49.9	100.0	75.1	50.1	0.0	-50.0
1	1.0	1.0	0.5	**0.1**	1.0	1.0	0.5	0.5	1.0	101	100.8	110.5	100.0	102.3	100.0	106.3	101.2	52.5	107.4	77.5	51.2	6.8	-47.9
2	1.0	1.0	0.5	**0.1**	1.0	1.0	0.5	0.5	1.0	98	93.2	113.1	78.8	129.1	82.9	99.0	128.1	54.7	89.6	70.0	39.0	-9.3	-44.6
3	1.0	1.0	0.5	**0.1**	1.0	1.0	0.5	0.5	1.0	97	88.1	113.8	63.7	136.6	75.8	92.7	146.6	52.4	82.0	67.4	36.1	-15.9	-46.2
4	1.0	1.0	0.5	**0.1**	1.0	1.0	0.5	0.5	1.0	97	85.0	113.9	55.8	138.9	72.4	89.1	158.0	50.6	78.4	65.3	35.4	-19.0	-47.6
10	1.0	1.0	0.5	**0.1**	1.0	1.0	0.5	0.5	1.0	96	81.6	114.0	47.8	140.3	68.0	84.6	172.3	48.2	74.2	62.6	35.1	-22.3	-49.6
Steady State	1.0	1.0	0.5	**0.1**	1.0	1.0	0.5	0.5	1.0	96	81.4	114.0	46.9	140.4	68.0	84.6	172.6	48.1	74.1	62.5	35.1	-22.4	-49.6

High Saving Rate ϕ = 0.9

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	1.0	1.0	0.0	**0.9**	1.0	1.0	0.5	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	50.0	100.0	75.0	50.0	0.0	-49.9
1	1.0	1.0	0.5	**0.9**	1.0	1.0	0.5	0.5	1.0	121	126.9	103.2	100.0	121.5	100.0	108.5	110.2	48.1	122.5	60.9	60.8	25.0	-50.9
2	1.0	1.0	0.5	**0.9**	1.0	1.0	0.5	0.5	1.0	117	129.4	106.3	104.4	154.4	91.6	112.2	121.6	57.9	108.8	62.3	46.8	16.4	-38.0
3	1.0	1.0	0.5	**0.9**	1.0	1.0	0.5	0.5	1.0	116	128.9	107.0	102.0	164.1	89.2	111.8	126.8	59.5	105.1	63.7	43.5	13.7	-35.7
4	1.0	1.0	0.5	**0.9**	1.0	1.0	0.5	0.5	1.0	116	128.0	107.2	99.2	167.5	88.2	110.9	129.9	59.4	103.6	63.6	42.7	12.4	-35.5
10	1.0	1.0	0.5	**0.9**	1.0	1.0	0.5	0.5	1.0	116	125.7	107.0	92.7	170.9	86.7	108.6	135.8	58.1	101.5	62.7	42.8	10.5	-36.7
Steady State	1.0	1.0	0.5	**0.9**	1.0	1.0	0.5	0.5	1.0	116	125.4	106.9	91.8	171.3	86.5	108.3	136.5	57.9	101.3	62.5	42.8	10.3	-36.9

Figure 2·5: Sensitivity Analysis

Note: δ is shocked from 0 in the initial steady state to .5. Changed parameters are highlighted.All Variables are indexed.

Perfect Substitutability in Spiritual Sector $\varepsilon_s = \infty$

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	**∞**	1.0	0.0	0.5	1.0	1.0	0.5	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	100.0	100.0	75.0	66.7	0.0	0.0
1	**∞**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	108	116.1	111.0	100.0	119.5	100.0	111.0	109.3	111.0	111.0	69.1	79.7	17.6	17.6
2	**∞**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	107	111.3	112.9	97.9	137.7	93.3	106.3	118.6	106.2	106.2	68.0	52.0	14.1	14.1
3	**∞**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	107	107.3	112.9	86.6	143.0	89.6	102.1	128.5	102.1	102.1	66.7	49.5	10.4	10.4
4	**∞**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	107	104.7	112.8	79.0	145.7	87.3	99.3	135.8	99.3	99.3	65.3	49.5	7.8	7.8
10	**∞**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	106	100.4	112.5	67.5	149.8	83.5	94.7	149.0	94.7	94.7	62.7	50.0	3.7	3.7
Steady State	**∞**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	106	100.1	112.5	66.7	150.1	83.2	94.3	150.0	94.3	94.3	62.5	50.0	3.4	3.4

Strong Complementarity in Spiritual Sector $\varepsilon_s = 0.5$

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	**0.5**	1.0	0.0	0.5	1.0	1.0	0.5	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	31.5	100.0	75.0	43.9	0.0	-68.4
1	**0.5**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	113	117.7	106.0	100.0	112.3	100.0	108.4	106.0	30.0	116.3	66.7	49.2	20.4	-68.9
2	**0.5**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	110	116.7	108.6	96.5	143.6	89.3	108.8	122.0	38.6	101.6	65.3	38.4	8.3	-58.8
3	**0.5**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	110	114.1	109.1	88.5	153.8	85.2	106.2	131.8	39.5	96.2	65.4	35.9	3.8	-57.4
4	**0.5**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	109	112.0	109.2	82.6	157.6	83.1	104.0	138.1	39.1	93.6	64.6	35.4	1.5	-57.6
10	**0.5**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	108	108.1	109.1	72.6	161.4	80.0	99.7	149.1	37.4	89.8	62.7	35.4	-1.7	-59.0
Steady State	**0.5**	1.0	0.5	0.5	1.0	1.0	0.5	0.5	1.0	108	107.8	109.1	71.9	161.6	79.7	99.4	150.0	37.3	89.5	62.5	35.4	-1.9	-59.1

Strong Complementarity in Corn Sector $\varepsilon_y = 0.8$

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	1.0	**0.8**	0.0	0.5	1.0	1.0	0.5	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	52.2	100.0	73.0	47.9	0.0	-47.8
1	1.0	**0.8**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	110	113.1	108.2	100.0	111.3	100.0	107.5	106.3	53.1	113.6	66.7	53.3	18.4	-44.6
2	1.0	**0.8**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	106	109.1	111.1	96.8	137.1	88.7	106.2	121.5	60.0	98.2	65.2	39.0	5.3	-35.7
3	1.0	**0.8**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	105	104.4	111.7	87.9	143.1	83.7	102.4	131.1	59.3	92.2	65.0	35.7	0.0	-35.7
4	1.0	**0.8**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	104	100.7	111.8	80.8	144.6	80.7	99.1	137.8	57.7	88.7	63.9	35.0	-3.1	-36.9
10	1.0	**0.8**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	101	92.3	111.9	65.8	145.0	74.2	91.4	153.6	53.3	81.7	60.8	34.7	-9.3	-40.7
Steady State	1.0	**0.8**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	101	90.9	111.9	63.7	145.0	73.3	90.2	156.2	52.7	80.6	60.2	34.7	-10.3	-41.4

Perfect Substitutability in Corn Sector $\varepsilon_y = \infty$

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	z	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	1.0	**∞**	0.0	0.5	1.0	1.0	0.5	0.5	1.0	100	100.0	100.0	100.0	100.0	-	100.0	100.0	45.5	100.0	80.0	54.6	0.0	-54.5
1	1.0	**∞**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	127	136.0	97.5	100.0	119.0	100.0	114.6	100.0	45.8	130.5	64.1	65.0	27.4	-55.3
2	1.0	**∞**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	123	144.1	99.5	94.6	163.6	95.0	120.9	100.0	53.6	124.0	66.7	56.8	23.5	-46.6
3	1.0	**∞**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	123	147.3	99.9	86.4	182.7	94.1	122.2	100.0	55.3	122.8	69.0	55.0	22.7	-44.7
4	1.0	**∞**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	123	148.7	100.0	81.0	191.5	93.9	122.4	100.0	55.6	122.5	69.6	54.7	22.6	-44.4
10	1.0	**∞**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	122	150.0	100.0	75.1	199.9	93.8	122.5	100.0	55.7	122.5	70.0	54.6	22.5	-44.2
Steady State	1.0	**∞**	0.5	0.5	1.0	1.0	0.5	0.5	1.0	122	150.0	100.0	75.0	200.0	93.8	122.5	100.0	55.7	122.5	70.0	54.6	22.5	-44.2

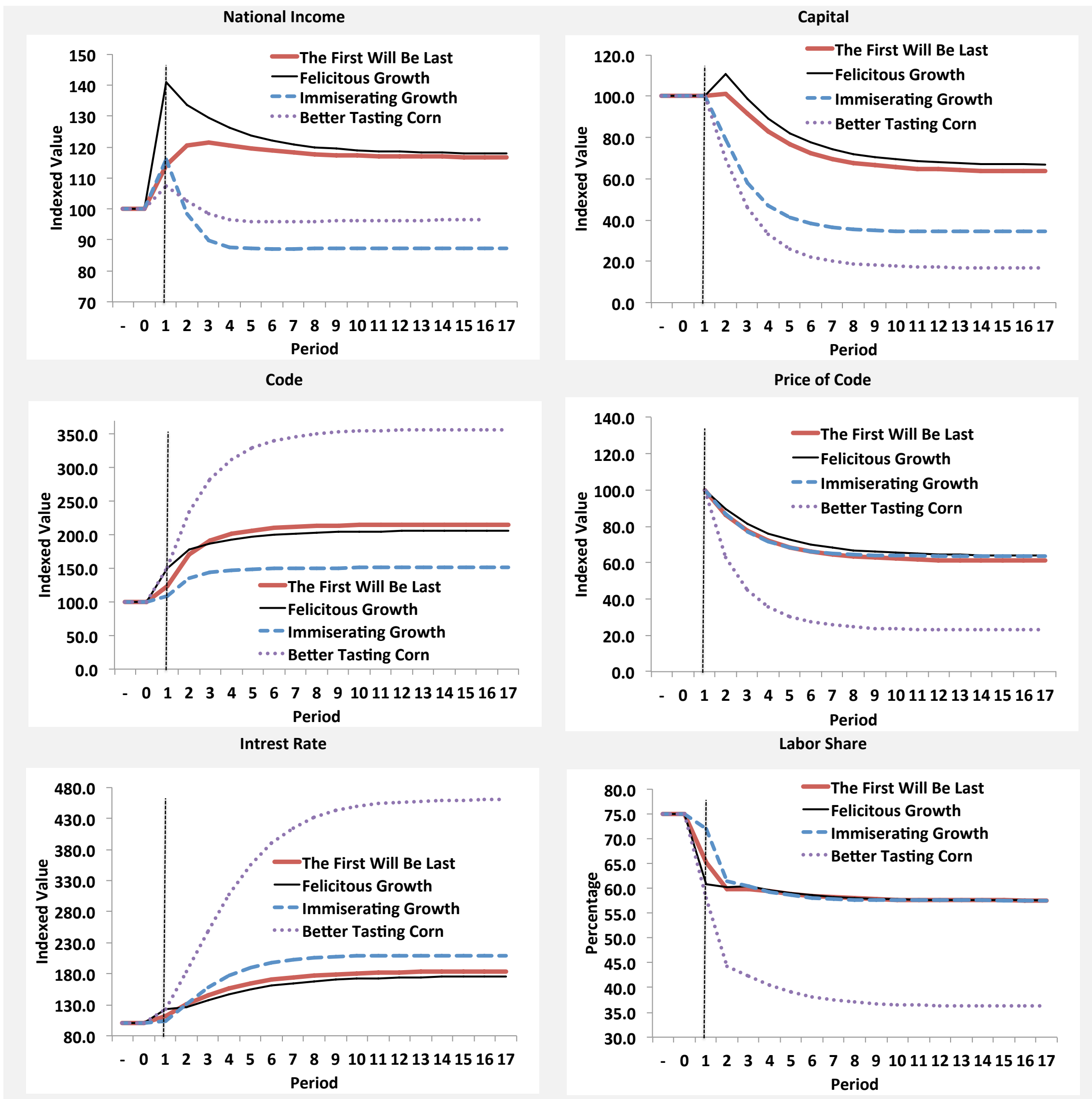
Code Writing Productivity Shock z Jumps from 1 to 1.5

Period	ε_s	ε_y	δ	ϕ	Labor High-Tech	Labor Low-Tech	κ	γ	**z**	Nat Income	Corn Output	Spirituality Output	K	A	p	q	r	Wage Hearts	Wage Heads	Labor Share	% Heads Coding	Compensating Differential Heads	Compensating Differential Hearts
Initial Steady State	1.0	1.0	0.0	0.5	1.0	1.0	0.5	0.5	**1.0**	100	100.0	100.0	100.0	100.0	-	100.0	100.0	50.0	100.0	75.0	50.0	0.0	-49.9
1	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	**1.5**	137	157.8	105.3	100.0	176.2	100.0	116.4	132.7	52.9	128.1	59.5	58.8	35.2	-44.2
2	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	**1.5**	133	162.3	108.6	112.3	221.7	92.0	122.4	140.5	64.5	116.2	61.2	44.6	25.9	-30.1
3	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	**1.5**	133	162.4	109.4	112.5	234.0	89.8	122.7	144.2	66.7	113.0	62.9	41.1	23.3	-27.3
4	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	**1.5**	133	161.8	109.5	110.9	237.6	89.0	122.3	146.4	66.9	111.8	63.0	40.2	22.3	-26.9
10	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	**1.5**	132	160.2	109.5	107.0	239.9	88.0	121.0	149.7	66.3	110.4	62.6	40.0	21.0	-27.3
Steady State	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	**1.5**	132	160.1	109.5	106.7	240.1	87.9	120.9	150.0	66.2	110.4	62.5	40.0	20.9	-27.4

Figure 2·6: Sensitivity Analysis Continued

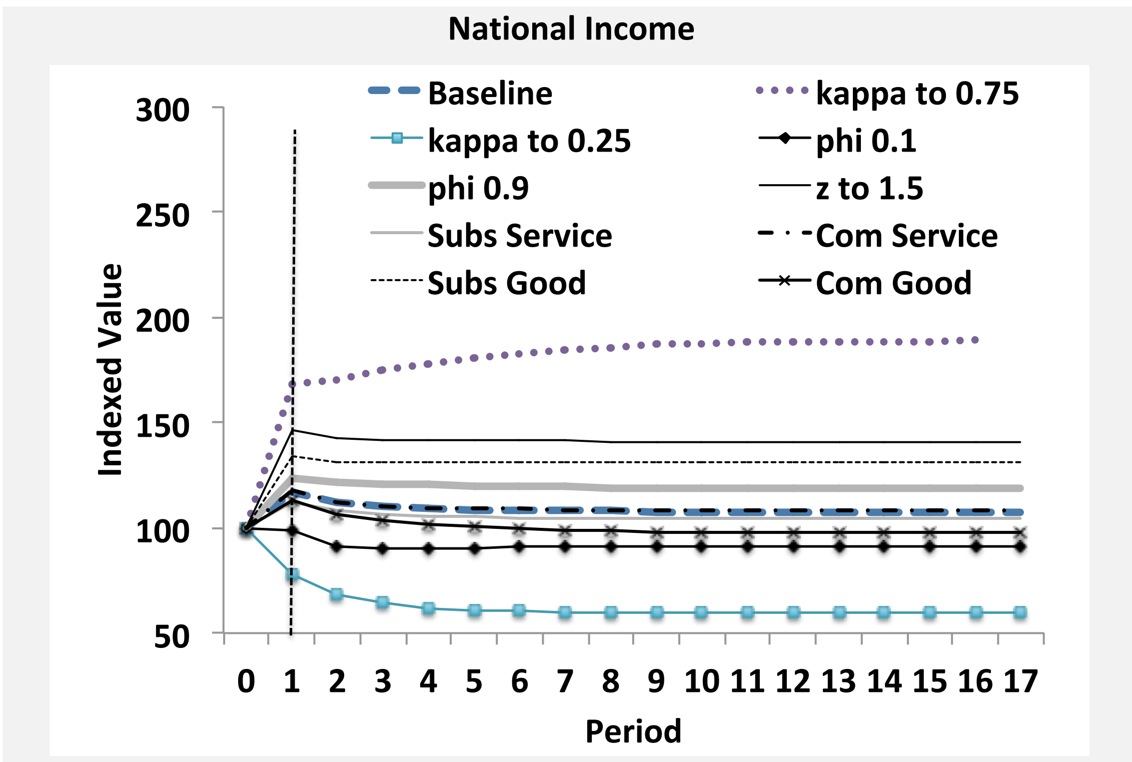
Note: δ is shocked from 0 in the initial steady state to .5. Changed parameters are highlighted.All Variables are indexed.

Figure 2·7: Comparing Four Case Studies



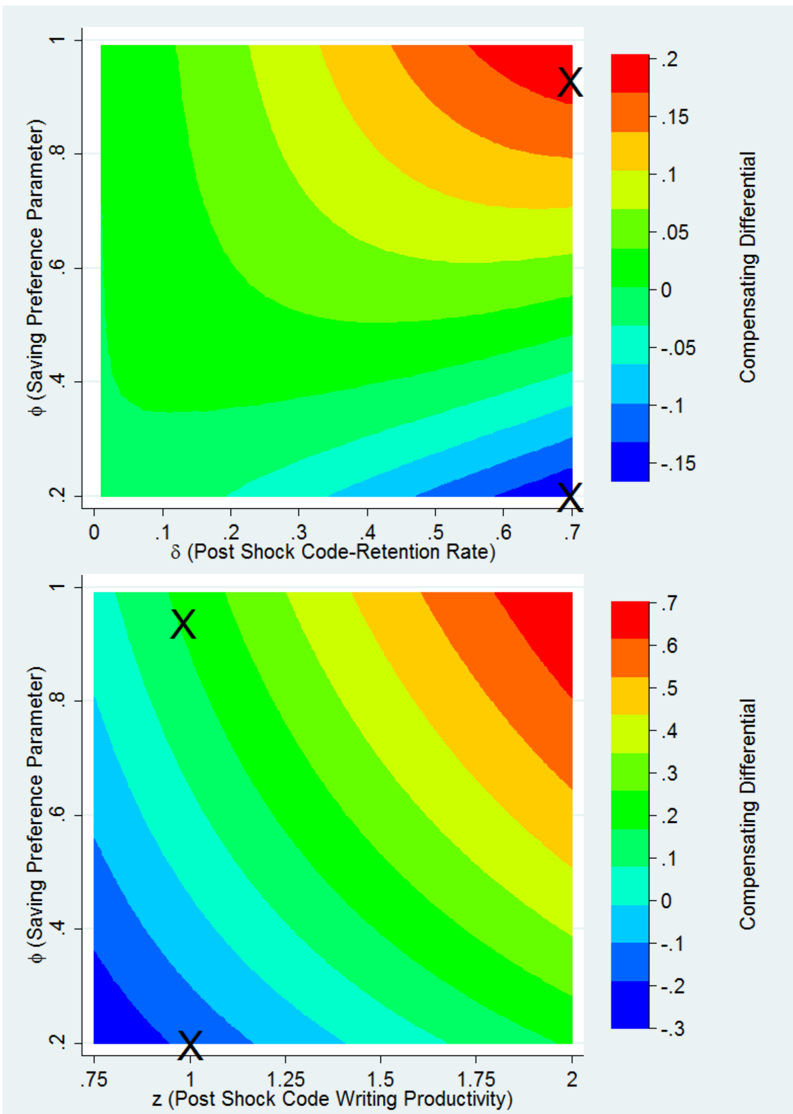
Note: Transition paths from the first 4 cases presented (immiserating growth, etc.) superimposed.

Figure 2·8: Illustration of the 10 sensitivity analysis cases superimposed.



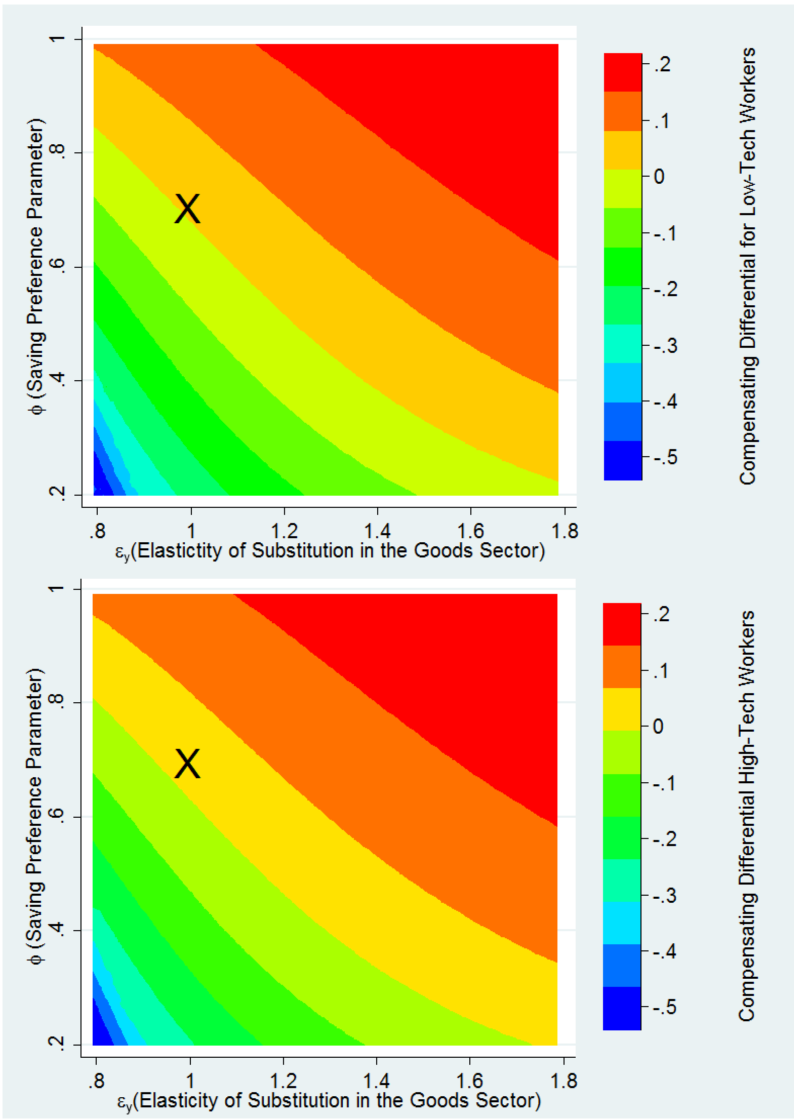
Note: "Subs" refer to cases in which the production technology of a sector is more substitutable. "Com" refer to cases in which the production technology is more complementary.

Figure 2·9: Long-Run Compensating Differential for Alternative Saving and Code-Retention and Productivity Shocks



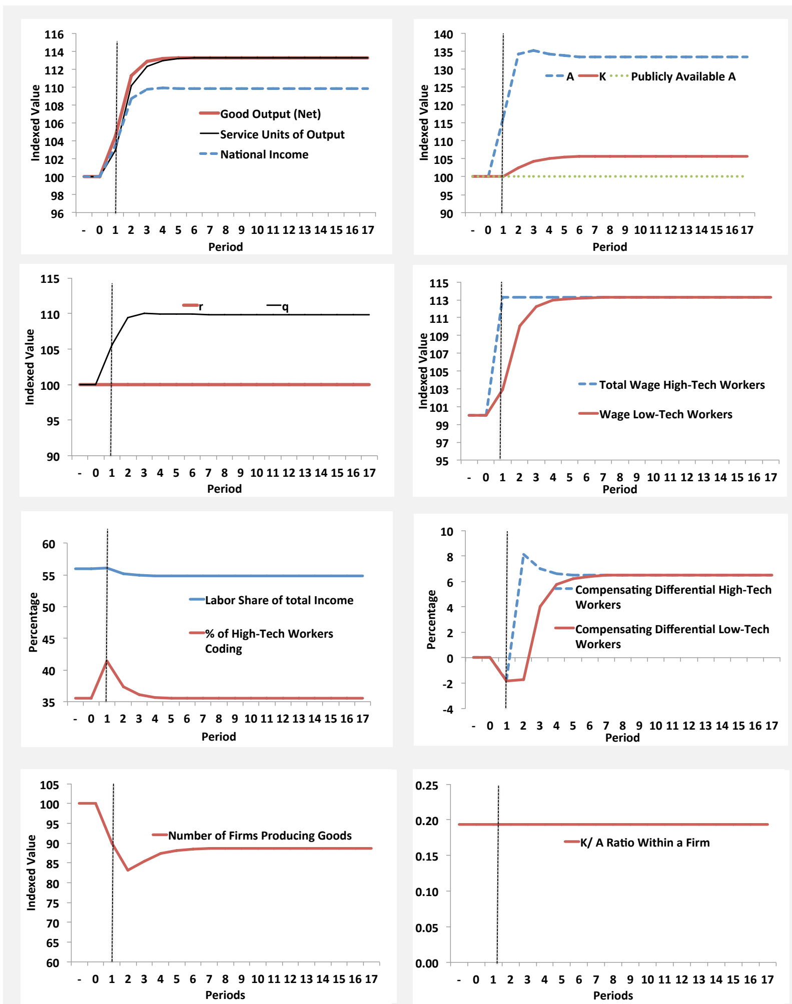
Note: "Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective post shock steady-state utility levels. Parameters not on axes are given in table 1. X's denote parameter combinations with transition paths discussed in the text.

Figure 2·10: Long-Run Compensating Differential for Alternative Saving and Elasticity of Substitution for Low and High-Tech Workers



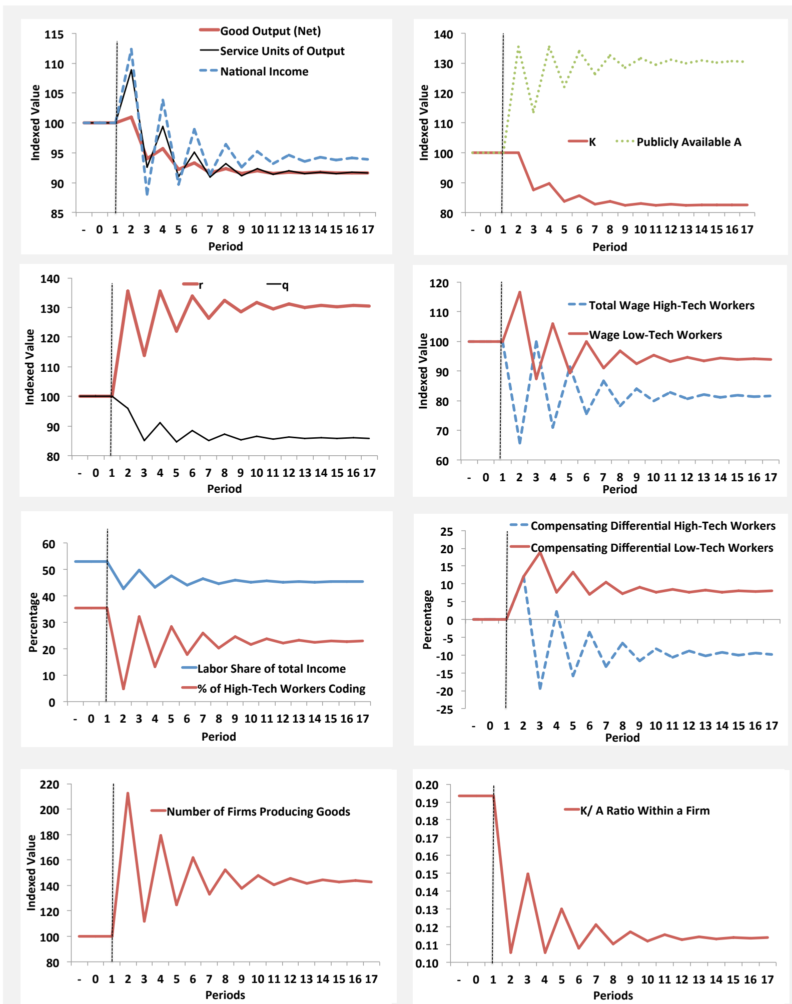
"Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective post shock steady-state utility levels. Parameters not on axes are given in table 2. X's denote parameter combinations with transition paths discussed in the text.

Figure 2·11: Rival, Excludable (Private) Code



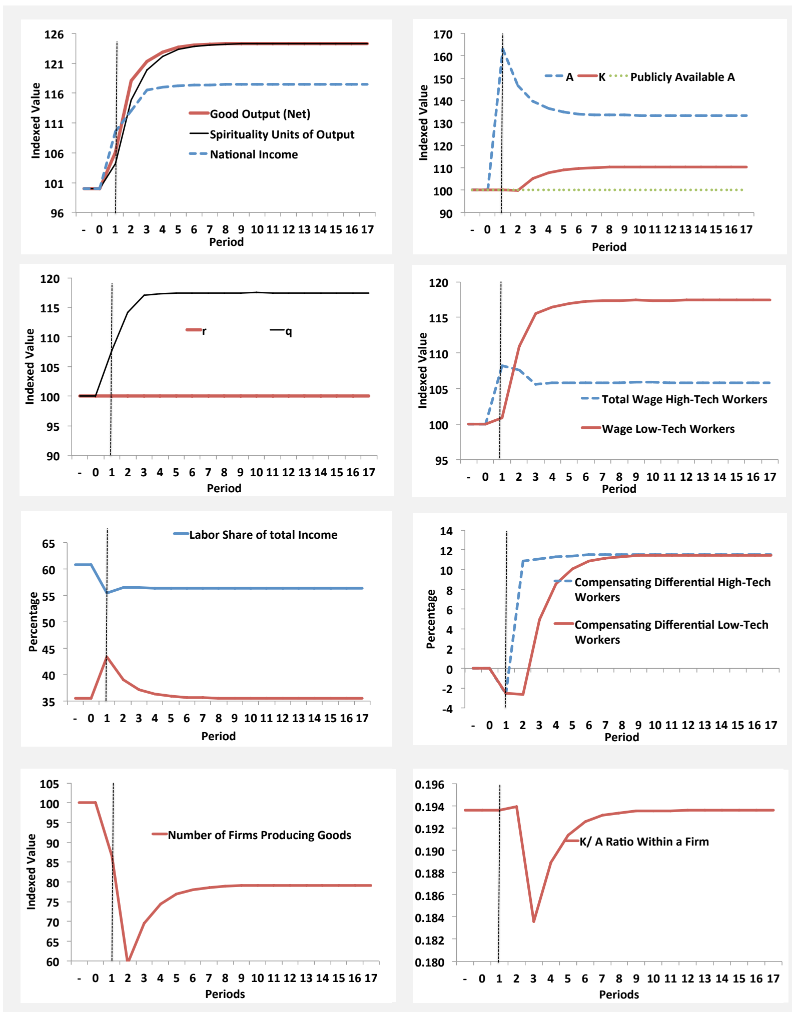
Note: Transition paths based on Table 4. "Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective transition utility levels. Service output is raw indexed output, not market value. Period 1 non-indexed prices in terms of the good are $r = 1.136$, $q = .382$, and $p = .117$.

Figure 2·12: Non-Rival, Non-Excludable (Public) Code



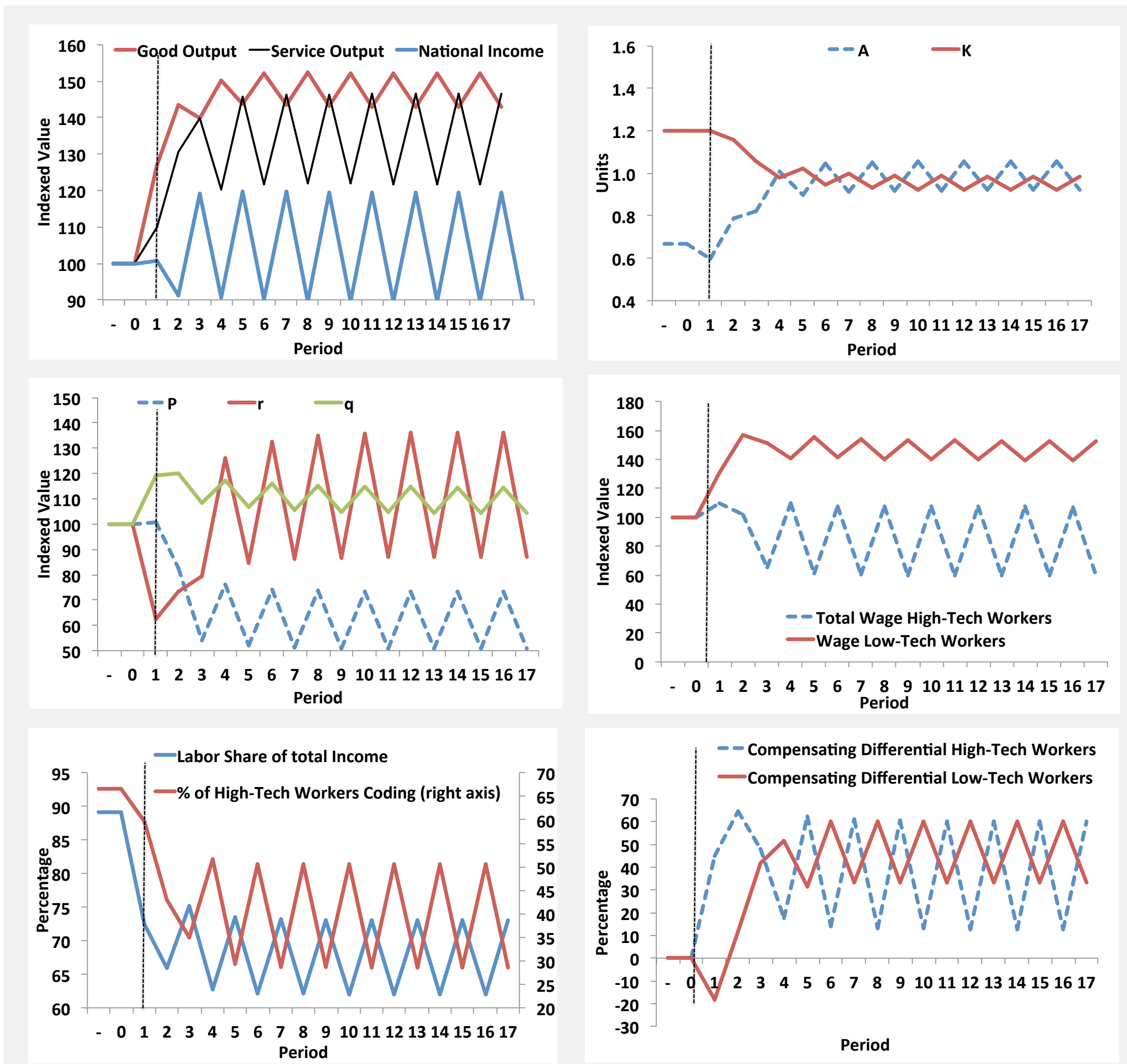
Note: Transition paths based on Table 4. All parameters are identical to Figure 10 except equations are modified as detailed in the text. "Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective transition utility levels. Service output is raw indexed output, not market value. Period 1 non-indexed prices in terms of the good are $r = 1.136$, $q = .353$, and $p = NA$.

Figure 2·13: Non-Rival, Excludable (Private) Code



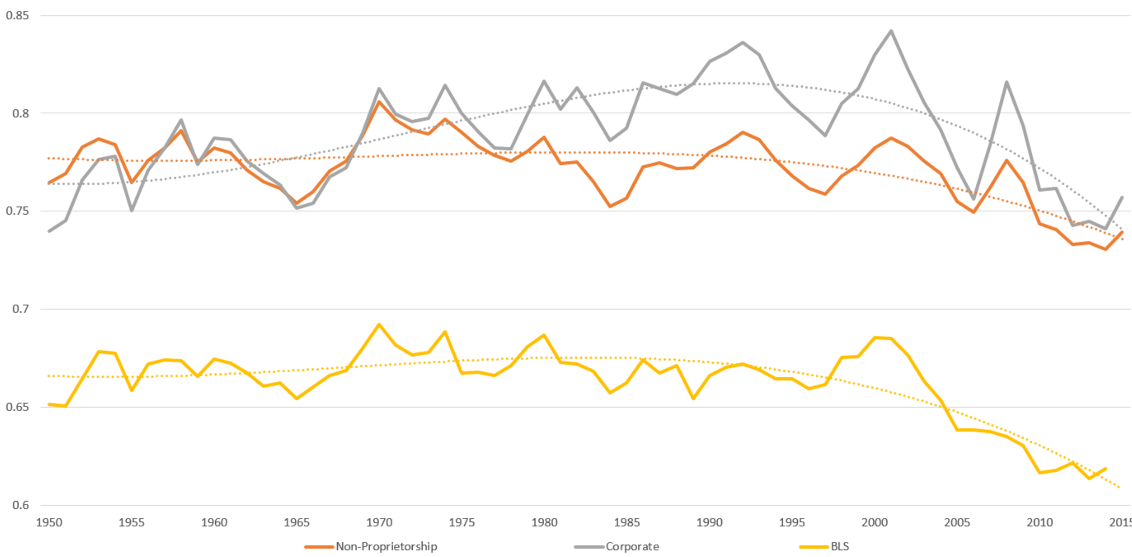
Note: Transition paths based on Table 4. All parameters are identical to Figure 10 except equations are modified as detailed in the text. "Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective transition utility levels. Service output is raw indexed output, not market value. Period 1 non-indexed prices in terms of the good are $r = 1.136$, $q = .393$, and $p = .164$.

Figure 2·14: Endogenous α



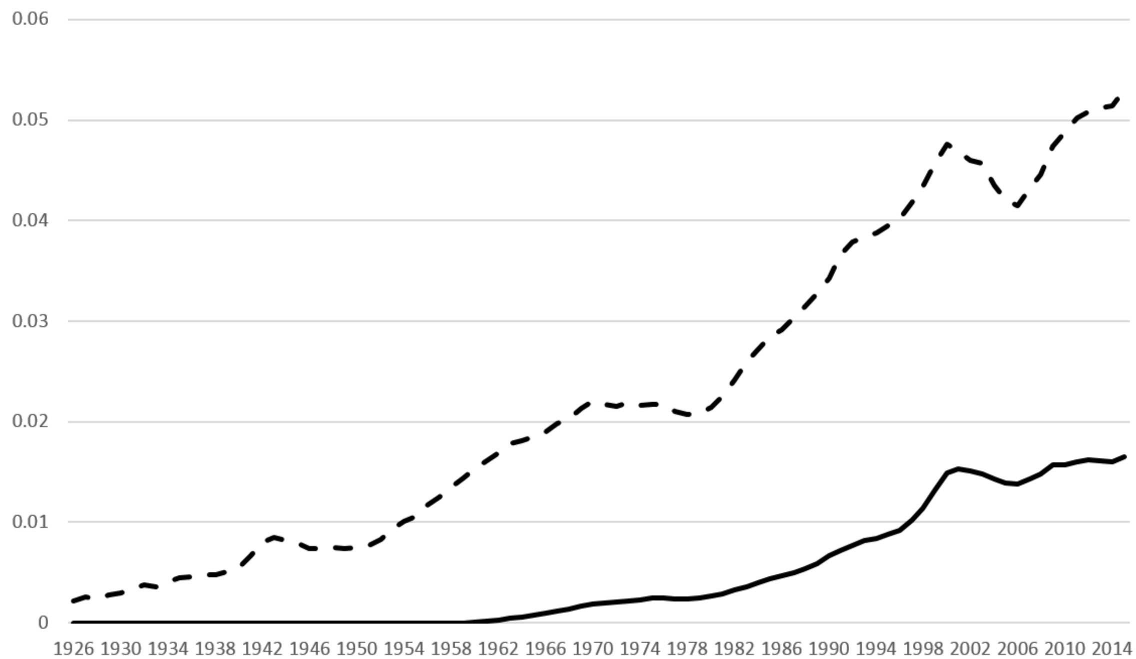
Note: Transition paths based on table 3."Compensating Differential" references the percentage change in initial steady-state consumption that would be needed for the utility levels of workers to equal their respective transition utility levels. Service and goods output are raw indexed output, not market value. Wage of low-tech workers is indexed to the initial steady state wage of high-tech workers.

Figure 2·15: Three Measures of Labor's Share of Income in the U.S.



Note: Three measures of the U.S. labor share. The orange curve, labor's share of non-proprietorship income, is calculated as employee compensation divided by national income at producer prices less proprietorship income (NIPA table 1.12, lines 2/(1-25+26-18). The gray curve, labor's share of income in the corporate sector, is calculated as corporate employee compensation divided by corporate business income less corporate taxes net of subsidies (NIPA table 1.13 lines 4/(3-9)). The yellow curve is the BLS's measure of labor share in the private business sector (from the BLS multi-factor productivity series). Dashed lines are fitted third-degree polynomials.

Figure 2·16: The Stock of Software and Software and R&D as a Share of U.S. Fixed Assets



Note: The stock of software (solid line) and software plus R&D assets (dashed line) as a share of total fixed assets (authors' calculation based on NIPA table 2.1).

Figure 2·17: U.S. Corporate Intangible Assets as a Share of U.S. Wealth

Note: U.S. corporate intangible assets as a share of U.S. wealth is calculated by subtracting the net worth of U.S. corporations from their equity value. Net worth is the replacement cost of fixed assets, plus the market value of other assets, less liabilities apart from owners' equity. This imputed value of intangible corporate assets (goodwill) is divided by total U.S. wealth (authors' calculation based on Federal Reserve financial accounts series Z.1).

Chapter 3

Robots: Curse or Blessing[26]

3.1 Introduction

The word robot comes from the Czech word 'robota', meaning forced labor. Ever since the term's invention by Karl Čapek in his 1920 dystopian science fiction masterpiece R.U.R, it has been associated with ambivalence about the power of automation. The play begins with the general manager of Rossum's Universal Robots discussing the potential of his assembled beings to raise living standards. He predicts that his robot laborers will lower the prices of goods to zero, ending toil and poverty forever. This plan hits a small snag when the robots decide to overthrow their masters and destroy all humans. But was the manager's economic forecast even correct in the first place?

This paper investigates the implications of capital investments, in the form of robots, which allow for production without labor. Our key finding is that an increase in robotic productivity will temporarily raise output, but, by lowering the demand for labor, can lower wages and consumption in the long run. In what we term a *paradox of robotic productivity*, innovations that increase the productivity of robotic investments can, after a generation, lower robotic and total output, and lower the well-being (lifetime utility) of all future generations. The mechanism for this immiserization is decreased wages of the workers with whom the robots compete. We find this immiserization is most likely when the future is heavily discounted, goods produced by robots are close substitutes for goods created by human labor, and when traditional capital is a more important factor in non-robotic production (so that the reduction of traditional capital has a larger adverse impact on wages). In our richest setting, increases in robotic productivity lower well-being until a threshold is reached. After reaching the threshold, the economy may grow indefinitely.

The fact that a rise in robotic productivity can immiserize future generations may seem paradoxical. After all, higher productivity enables society to produce more output from the same quantity of inputs. If the market response to robotic innovations does not lead to a positive result, this suggests that there may be an role for government intervention. We show this intuition to be correct. Immiserization may be overcome through redistributive policies of the state.

The paper proceeds as follows. A brief literature review puts current concerns about automation in a historic context and surveys the research on robots and growth. Section 3 introduces a basic overlapping generations setting in which the generational impact of robots can be considered. Section 4 investigates the one-sector version of the model, and section 5 analytically considers the two-sector version. Section 6 gives a numerical analysis of the two-sector model. Section 7 concludes.

3.2 Literature Review

Even before the birth of modern science fiction, academics and ordinary people have been concerned about the potential downsides of technological growth.[27] The English Luddites of the late 18th and early 19th centuries famously organized raids and riots against the industrial machines they felt were taking their jobs. In the second half of the 19th century, (Marx, 1887) bemoaned the fact that under capitalism "all methods for raising the social productivity of labour are put into effect at the cost of the individual worker." In the first half of the 20th century (Keynes, 1963) cautioned against overreaction to "technological unemployment", which, while painful for displaced workers, was merely a "temporary phase of maladjustment." Similarly, Schumpeter championed the "creative destruction" of capitalism, in which older ways of doing work are, not without pain, superseded by advances in technology as new types of more productive work are created.

In the economic prosperity of the post-war era, the views of technological optimists generally held sway. However, recent wage stagnation and growing inequality across the developed world have led economists to take another hard look at technological growth. (Autor et al., 2003), (Acemoglu and Autor, 2011), and (Autor and Dorn, 2013) trace recent declines in employment and wages of middle skilled workers to the development of smart machines. (Katz and Margo, 2014) points to similar *labor polarization* during the early stages of Americas industrial revolution. (Goos et al., 2010) offer additional supporting evidence for Europe. (Sachs and Kotlikoff, 2012) present a model in which robots immiserize future generations, a precursor of the models studied in this paper. However, (Schmitt et al., 2013) argue that robots cant be blamed for post-1970s U.S. job polarization given the observed timing of changes in relative wages and employment. A literature inspired by Nelson and Phelps (1966) hypothesizes that inequality may be driven by skilled workers more easily adapting to technological change, but generally predicts only transitory increases in inequality.

A potential implication of our model is a decline, over time, in labors share of national income. U.S. national accounts record a stable percent share of national income going to labor during the 1980s and 1990s. But starting in the 2000's labors share has dropped significantly. Benedict and Osborne (2013) try to quantify prospective human redundancy arguing that over 47 percent of current jobs will likely be automated in the next two decades. Hemous and Olson (2014) calibrate a model in which capital can substitute for low-skilled labor while complementing high-skilled labor to explain trends in the labor share of income and inequality.

The lessons of our model are also related to the endogenous growth literature. In Rebelos (1991) AK model, sustained per capita output growth occurs so long as there are no decreasing returns to scale in production. This model complemented Romer (1990) which included open ended growth driven by endogenous technological development in the tradition of learning by doing proposed by Arrow (1962).

There are several models that include a potential for welfare improving intergenerational transfers. Two papers that with mechanisms more similar to this one are Sachs and Kotlikoff (2013) and Benzell *et. al.* (2015). These papers also posit that technological changes may immiserize future generations through the mechanism of reduced wages.

3.3 The Model Framework

The essential quality of robots, as we define them, is that they allow for output without labor. To produce a unit of output from robotic technology, entrepreneurs need only make a capital investment. Innovation in robotic production can therefore change labor's share of national income. In a model with an infinitely lived representative consumer, this is unlikely to have major effects. However, if those earning labor and capital income have different propensities to consume, then a change in labor's share of income can have important effects on saving and investment. We attempt to capture this effect in the simplest possible setting.

The setup is an overlapping generations (OLG) model with two cohorts. This allows for labor's share of income to have a dynamic effect and straightforward generational welfare analysis.

Households

All individuals live for two periods, working, saving and consuming while young, and consuming while old. Workers in this economy maximize a lifetime utility function of the form

$$U_t = \phi u(\vec{c}_{1,t}) + (1-\phi)u(\vec{c}_{2,t+1}), \tag{3.1}$$

where $\vec{c}_{1,t}$ and $\vec{c}_{2,t+1}$ are vectors of goods consumed by a household in the first and second periods of life, and $u(\cdot)$ is a within-period homothetic utility function. Henceforth, we assume within-period utility is logarithmic, $u(\vec{c}_t) = ln(v(\vec{c}_t))$, where v is Cobb-Douglas with constant returns to scale. There is no leisure.

A generation maximizes U_t subject to its lifetime budget constraint, which in general may include government taxes and transfers.

$$w_t L_t + G_t = \vec{p}_t \vec{c}_{1,t} + \frac{\vec{p}_{t+1}\vec{c}_{2,t+1}}{1 + [r_{t+1}(1-\tau_t)]}, \tag{3.2}$$

where $\vec{p}_t$ is a vector of prices, w_t is the wage, G_t is the size of government grants to the young, $1 + r_t$ the interest rate, and τ_t is the capital income tax rate. For convenience, define the net income of the young as the sum of their labor income and any government transfer, and the net interest rate of the old as net of the government capital income tax. Thus,

$$w_t^N = w_t L_t + G_t, \tag{3.3}$$

and

$$r_t^N = r_t(1-\tau_t). \tag{3.4}$$

Utility maximization leads to the well-known result that saving, S_t, equals a fixed fraction $(1-\phi)$ of youth income,

$$S_t = (1-\phi)(w_t^N). \tag{3.5}$$

Households allocate savings with perfect foresight between available types of physical assets to maximize returns.

3.4 The One-Sector Model

In this model framework the performance of labor markets is strongly linked to the extent goods produced with human effort are replaceable by those that robots create. When the outputs of robots are close substitutes for production by humans and machinery, an increase in robotic productivity is likely to reduce demand for labor. A fall in labor demand may trigger further declines in wages, saving, and economic well-being. However, to the extent that workers produce outputs that not perfectly substituted for with the outputs of robots, workers will experience a rise in demand for their products, and this can result in a virtuous circle of rising wages, savings, and production.

First we consider the one-sector version of the model. There is only one good, and it is produced using both traditional and robotic production technologies.

Supply in the One-Sector Model

In the one-sector model, there are two perfectly competitive types of firms. Time t production of the consumption and investment good with the traditional output technology, $X_{m,t}$, follows

$$X_{m,t} = D_{X,t} M_{X,t}^{\epsilon} L_{X,t}^{1-\epsilon}, \tag{3.6}$$

where $M_{X,t}$ is the amount of machines rented by these firms, $L_{X,t}$ is the amount of labor hired, ϵ is a Cobb Douglas parameter, and $D_{X,t}$ a total factor productivity term. Production by robotic firms follows

$$X_{r,t} = \Theta_t R_t, \tag{3.7}$$

where $X_{r,t}$ is the output of these firms, R_t is the amount of robots rented by these firms, and Θ_t is the robotic productivity.

Factor demands for robots, machines, and labor reflect profit maximization

$$\max_{M_{X,t} L_{X,t}} X_{m,t}(M_{X,t}, L_{X,t}) - w_t L_{X,t} - m_t M_{X,t} \tag{3.8}$$

and

$$\max_{R_t} X_{r,t}(R_t) - \rho_t R_t, \tag{3.9}$$

where m_t is the rental rate for machines and ρ_t is the rental rate for robots.

These yield the first order conditions

$$w_t = (1-\epsilon) D_{X,t} M_{X,t}^{\epsilon} L_{X,t}^{-\epsilon}, \tag{3.10}$$

$$m_t = \epsilon D_{X,t} M_{X,t}^{\epsilon-1} L_{X,t}^{1-\epsilon}, \tag{3.11}$$

and

$$\rho_t = \Theta_t. \tag{3.12}$$

Households in the One-Sector Model

Utility is logarithmic in consumption of the one good.

$$u(x_t) = ln(x_t), \tag{3.13}$$

Household demands for consumption and investment satisfy

$$x_{1,t} = \phi w_t^N \tag{3.14}$$

and

$$x_{2,t} = (1 + r_t^N)K_t, \tag{3.15}$$

where K_t is capital of any type owned by the old.

Equilibrium in the One-Sector Model

The total output of the economy is the sum of the outputs of the two types of firms,

$$X_t = X_{m,t} + X_{r,t}. \tag{3.16}$$

The one-sector model is in equilibrium when the market for goods clears,

$$X_t = x_{1,t} + x_{2,t} + S_t, \tag{3.17}$$

the labor market clears,

$$L_{X,t} = L_t, \tag{3.18}$$

the government is balancing its budget,

$$G_t = r_t \tau_t K_t, \tag{3.19}$$

and the market for investments clears,

$$S_t = K_{t+1} = M_{X,t+1} + R_{X,t+1}, \tag{3.20}$$

as capital depreciates fully each period.

Finally, investment seeks maximum returns in the subsequent period with perfect foresight. Here we are only interested in the case where robots are productive enough to be used, so investment must equalize the rate of return of both forms of capital. Therefore,

$$1 + r_t = m_t = \rho_t = \Theta_t. \tag{3.21}$$

One-Sector Equilibrium Analysis

Consider the case where $D_{X,t} = 1$ and $L_t = 1$ in all periods.

Combining first order equations yields

$$w_t = (1 - \epsilon)(\frac{\epsilon}{\Theta_t})^{\frac{\epsilon}{1-\epsilon}}. \tag{3.22}$$

Note that a rise in robot productivity reduces the wage. The reason is that higher Θ shifts investment from machines into robots. This lowers the capital-labor ratio in X_m firms, decreasing the marginal productivity of workers. The wage is not influenced by the capital stock, because both the quantity of labor and the interest rate are fixed by factors outside the traditional firms. This in turn fixes the amount of capital in traditional firms and therefore the wage.

We can write the indirect utility function in terms of Θ_t and Θ_{t+1}. Ignoring constant terms, and assuming no transfers ($G_t = \tau_t = 0$) we have

$$U_t = lnw_t + (1 - \phi)ln(1 + r_{t+1}), \tag{3.23}$$

or equivalently,

$$U_t = \frac{-\epsilon}{1 - \epsilon} ln\Theta_t + (1 - \phi)ln\Theta_{t+1}. \tag{3.24}$$

Notice that robot productivity has two opposing effects on lifetime utility. High Θ_t

lowers the wage while high Θ_{t+1} raises the returns to saving. The negative wage effect tends to dominate the saving effect when the capital share of income (ϵ) in traditional firms is large, because this measures the importance of machines in complementing the labor or workers. Immiserization is also more likely when the discount rate ϕ is higher, because a high ϕ means that the utility value of higher returns to saving is low.

Consider a one-step permanent rise of Θ at time T. That is for $t < T$, $\Theta_t = \Theta^L$ and for $t \geq T$, $\Theta_t = \Theta^H > \Theta^L$. The lifetime utility of an individual born in t is

for $t < T - 1$

$$U_t = \frac{-\epsilon}{1-\epsilon} ln\Theta^L + (1-\phi) ln\Theta^L, \tag{3.25}$$

when $t = T - 1$

$$U_t = \frac{-\epsilon}{1-\epsilon} ln\Theta^L + (1-\phi) ln\Theta^H, \tag{3.26}$$

and if $t > T - 1$

$$U_t = \frac{-\epsilon}{1-\epsilon} ln\Theta^H + (1-\phi) ln\Theta^H. \tag{3.27}$$

The rise in robot productivity in period T must raise the welfare of generation $T - 1$. For that generation, the rise of robot productivity was too late to impact their wage. However, the return on their saving is increased by the rise in robotic productivity in period T. Generation $T - 1$, in other words, will enjoy high wages when young and high retirement income when old. Generations T and after will not be so lucky. For them, the positive effect of better robots is at least partially offset by lower wages.

An increase in robotic productivity will induce long-run immiserization[28] as long as

$$\frac{\epsilon}{1-\epsilon} > (1-\phi). \tag{3.28}$$

If (28) holds, the wage effect dominates and leads to a decline in lifetime utility. Only a single generation benefits from the rise of robot productivity, specifically the generation born in the period before the improvement in robot productivity. That generation benefits from higher returns to saving without incurring the negative shock of lower wages.

Ensuring that all generations benefit from the rise in Θ

Could a managed rise of robots lead to a better long-run outcome? It is clear that markets alone are not sufficient to ensure that a rise of robot productivity raises the well-being of future generations. However, it seems likely that a pure rise in productivity, by pushing out the production possibility frontier, can be made into a rise in lifetime utility for all generations with the right kind of government intervention. To insure a better outcome, the income of the young should be augmented by redistribution from the old.

Here's how to turn the robotics innovation in time T into a rise in well-being for all generations from time T-1 onward.

In every period T and after, the government levies a tax on the capital income of retirees and transfers the proceeds as a grant G_t to the young. Let the government set the grant equal to the decline of the wage caused by the rise of Θ. Let w^H be the market wage associated with Θ^H and w^L be the market wage associated with Θ^L. Then necessarily, $w^L > w^H$. The grant mechanism will function as follows: For $t > T - 1$

$$G_t = w_t^L - w_t^H. \tag{3.29}$$

To pay for this grant, the government levies a capital-income tax at rate τ_t on the old in each period. With saving S_t, pre-tax capital income is given by $\Theta^H S_t$. Therefore, the tax rate should be set such that for $t \geq T$

$$G_t = (\Theta^H - 1)\tau_t K_t. \tag{3.30}$$

Of course, savers anticipate this capital income tax and plan their inter-temporal spending decisions accordingly. Instead of earning a rate of return Θ^H, savers will earn a net-of-tax rate of return $(1 + r_{t+1}^N) = 1 + (\Theta^H - 1)(1 - \tau_t)$. Because of their logarithmic preferences this change in rate of return does not change their saving behavior. The indirect lifetime utility function can be re-written in terms of youth net-of-transfer income w_t^N and r_{t+1}^N. Since policy fixes the disposable wage at w_t^L we have, ignoring constant terms,

$$U_t^L = ln(w_t^L) + (1 - \phi)ln(1 + r_{t+1}^N). \tag{3.31}$$

Every generation will be better off when Θ rises to Θ^H, as net of tax lifetime budget constraints must be larger than when Θ^L.

When Θ rises, it is easy to see that X_t rises instantaneously as well. This is because the level of capital is unchanged, but its productivity has increased. Now, consider total output from the perspective of factor income. Since there are no profits, $X_{r,t} = \Theta R_t$ and $X_{m,t} = w_t + \Theta M_t$, we have that $X_t = w_t + \Theta(R_t + M_t) = w_t + \Theta S_{t-1}$. By (5), S_t depends only on the net income of the young w_t^N. The transfer system keeps the disposable wage equal to w_t^L, so saving S_t also remains unchanged when Θ rises. When Θ rises, the overall rise of X_t ensures that $w_t^H + \Theta^H S_t > w_t^L + \Theta^L S_t$. Therefore, $w_t^H - w_t^L + \Theta^H S_t > \Theta^L S_t$. Since $w_t^L - w_t^H$ equals G_t, which is also equal to $(1 + (\Theta^H - 1)\tau_t)S_{t-1}$, we find that $(1 + (\Theta^H - 1)\tau_t)S_{t-1} > \Theta^L S_t$. Hence, $(1 + r_{t+1}^N) = (1 + (\Theta^H - 1)\tau_t) > \Theta^L$.

This reasoning establishes a key result. By taxing the capital of the old, and transferring the proceeds to the young, the government keeps the net income of the young unchanged while the net-of-tax rate of return on saving is higher. Therefore, the rise of robot productivity to Θ^H combined with the fiscal transfer system raises the well-being of all generations compared with the utility when productivity equals Θ^L.

The result is important in light of discussions as to whether robotics will necessarily raise or lower well-being. The answer is that higher productivity is a potential gain for all generations, but only if government undertakes redistributive policies to ensure that indeed all generations benefit. Without such redistribution, it is possible, we have seen, that the robotics innovation improves the well-being of just one generation, while lowering the lifetime well-being of all future generations.

3.5 The Two-Sector Model

An important critique of the one-sector model is that it takes robotic and labor produced goods as identical. In reality, there are many goods that robots cannot create or might only create with greatly diminished productivity. Examples include many personal services that depend intrinsically on human-to-human interactions, and various kinds of creative activities not reducible to computer algorithms, e.g. in the arts.

To allow for complementarity in consumption between robotic and non-robotic goods, we move to a richer two-sector setting. Here two goods are produced and consumed, but only one is automatable (i.e. eligible for production by robots). The core insights of the one-sector model are maintained, but complex additional dynamics emerge.

Supply in the Two-Sector Model

In the two-sector model, there are three types of firms. The X sector is identical to the one-sector case, so

$$X_{m,t} = D_{X,t} M_{X,t}^{\epsilon} L_{X,t}^{1-\epsilon}, \tag{3.32}$$

and

$$X_{r,t} = \Theta_t R_t. \tag{3.33}$$

In addition there are firms producing the consumption good Y with technology

$$Y_t = D_Y M_{Y,t}^{\alpha} L_{Y,t}^{1-\alpha}, \tag{3.34}$$

where Y_t is the output of these firms at time t, $M_{Y,t}$ is the amount of machines rented by these firms, $L_{Y,t}$ is the amount of labor they hire, α is capital's share of output in production of Y, and D_Y is a total factor productivity term.

We will refer to the X sector as the robotic or automatable sector interchangeably. We will refer to the Y sector as the non-robotic, non-automatable, or traditional sector interchangeably.

Factor demands for robots, machines, and labor reflect

$$\max_{M_{X,t} L_{X,t}} X_{m,t}(M_{X,t}, L_{X,t}) - w_t L_{X,t} - m_t M_{X,t}, \tag{3.35}$$

$$\max_{R_t} X_{r,t}(R_t) - \rho_t R_t, \tag{3.36}$$

and

$$\max_{M_{Y,t} L_{Y,t}} p_t Y_t(M_{Y,t}, L_{Y,t}) - w_t L_{Y,t} - m_t M_{Y,t}, \tag{3.37}$$

where p_t is the price of the non-automatable good in terms of the potentially robotic good. All factor inputs must be non-negative.

Assuming that the non-negative input constraint does not bind for any type of firm, first order conditions are

$$w_t = (1-\epsilon_t)D_{X,t}M_{X,t}^{\epsilon}L_{X,t}^{-\epsilon}, \tag{3.38}$$

$$w_t = (1-\alpha_t)p_tD_{Y,t}M_{Y,t}^{\alpha}L_{Y,t}^{-\alpha}, \tag{3.39}$$

$$m_t = \epsilon_tD_{X,t}M_{X,t}^{\epsilon-1}L_{X,t}^{1-\epsilon}, \tag{3.40}$$

$$m_t = \alpha p_tD_{Y,t}M_{Y,t}^{\alpha-1}L_{Y,t}^{1-\alpha}, \tag{3.41}$$

and

$$\rho_t = \Theta_t. \tag{3.42}$$

Households in the Two-Sector Model

Within period utility is logarithmic in the Cobb-Douglas combination of the two types of consumption.

$$u_t(x_t, y_t) = \beta ln(x_t) + (1-\beta)ln(y_t). \tag{3.43}$$

This specification implies that individuals want to spend constant shares of their consumption on the automatable and non-automatable good.[29]

The household budget constraint is

$$w_t^N = x_{1,t} + p_ty_{1,t} + \frac{x_{2,t+1} + p_{t+1}y_{2,t+1}}{1+r_{t+1}^N}. \tag{3.44}$$

Household demands for consumption and investment at time t satisfy

$$x_{1,t} = \beta\phi w_t^N, \tag{3.45}$$

$$x_{2,t} = (1 + r_t^N)\beta K_t, \tag{3.46}$$

$$y_{1,t} = \frac{(1-\beta)\phi w_t^N}{p_t}, \tag{3.47}$$

$$y_{2,t} = \frac{(1-\beta)(1 + r_t^N)K_t}{p_t}, \tag{3.48}$$

and

$$S_t = (1-\phi)w_t^N, \tag{3.49}$$

where K_t is capital of any type owned by the old.

Equilibrium in the Two-Sector Model

The potentially robotic good is an investment and consumption good, while the non-robotic sector produces only a consumption good. Capital depreciates fully each period. Equilibrium requires

$$X_t = X_{m,t} + X_{r,t}, \tag{3.50}$$

$$X_t = x_{1,t} + x_{2,t} + S_t, \tag{3.51}$$

$$Y_t = y_{1,t} + y_{2,t}, \tag{3.52}$$

$$L_t = L_{X,t} + L_{Y,t}, \tag{3.53}$$

$$G_t = r_t \tau_t K_t, \tag{3.54}$$

and

$$S_t = K_{t+1} = M_{X,t+1} + M_{Y,t+1} + R_{X,t+1}. \tag{3.55}$$

Phases of the Two Sector Economy

As in the one-sector model, investors allocate capital with perfect foresight to maximize returns. In this decision the non-negative capital constraint can bind in two ways. When robotic productivity and capital stocks are low, it is inefficient to invest in robots, and firms use only traditional manufacturing in the automatable sector. When robotic productivity and capital stocks are high, traditional manufacturing is not competitive in the X sector, and only robotic investments are made. There is also a range of values for Θ_t and K_t where both traditional manufacturing and robots are used in the automatable sector. In this intermediate case, both $M_{t,x} > 0$ and $R_t > 0$.

Taking $G_t = \tau_t = 0$, $M_{t,x} > 0$ implies that

$$K_t < \left((1-\epsilon) \left[\frac{D_x}{\theta_t} \right]^{\frac{1}{1-\epsilon}} \epsilon^{\frac{\epsilon}{1-\epsilon}} L \right) \frac{(1-\phi(1-\alpha)(1-\beta))}{(1-\beta)(1-\alpha)} \tag{3.56}$$

And $R_t > 0$ requires

$$K_t > \left((1-\epsilon) \left[\frac{D_x}{\theta_t} \right]^{\frac{1}{1-\epsilon}} \epsilon^{\frac{\epsilon}{1-\epsilon}} L \right) \frac{\epsilon - (1-\beta)(\epsilon-\alpha)\phi}{(1-\epsilon)+(\epsilon-\alpha)(1-\beta)}. \tag{3.57}$$

When (56) is violated, no machines or labor are used in the automatable sector. When (57) is violated, the model reduces to the normal two-sector OLG and no robots are used. Note that when $D_x = 0$ it must be the case that no labor is used in the automatable sector as its productivity must be zero. As $\theta_t \to 0$, there is never enough capital to make robotic production competitive and only the first case is possible. The paper proceeds by considering these three cases in turn.

The paper proceeds by considering these three cases in turn.

Case 1: No Robots Used

When capital stocks per unit of labor are low, the marginal productivity of capital is high. If capital stocks per unit of labor are low enough, investing all savings in the form of traditional machines will yield a higher interest rate than Θ, the rate of return on robots. In such periods, the interest rate will not be fixed by Θ but will be a function of capital stocks. It must be that $1 + r_t > \Theta_t$. The economy reduces to the well-understood two-sector OLG case.

An economy which does not use robots can shift to use of robots in two ways of interest. First, capital may accumulate to the extent that using some as robots may be more efficient than using them as machines (which face decreasing returns). Second, an increase in θ can increase the right hand side enough such that (56) is no longer satisfied.

As this type of economy is well understood, we will now move on to cases of greater interest.

Case 2: Mixed Production of the Automatable Good

When both (56) and (57) hold, robots and traditional manufacturing compete head to head in the creation of the same product. $R_t, L_{Y,t}$, and $L_{X,t} > 0$. Optimization requires $1 + r_t = \Theta_t$.

Insights from the one-sector model carry over into this case. Assume for now that there are no transfers. Combining first order conditions, the price of the non-automatable good may be written as

$$p_t = \frac{\Theta_t}{\alpha D_{Y,t}}[\frac{M_{t,y}}{L_{t,y}}]^{1-\alpha}. \tag{3.58}$$

Factor demands also imply

$$\frac{M_{t,y}}{L_{t,y}} = \frac{\alpha(1-\epsilon)}{\epsilon(1-\alpha)}\frac{M_{t,x}}{L_{t,x}}, \tag{3.59}$$

and

$$\frac{M_{t,x}}{L_{t,x}} = \Big(\frac{\epsilon D_{X,t}}{\Theta_t}\Big)^{\frac{1}{1-\epsilon}}. \tag{3.60}$$

This allows for the rewriting of prices in terms of Θ_t.

$$p_t = \Theta_t^{\frac{\alpha-\epsilon}{1-\epsilon}} \frac{1}{\alpha D_{Y,t}} \Big(\frac{\alpha(1-\epsilon)}{\epsilon(1-\alpha)}\Big)^{1-\alpha} (\epsilon D_{X,t})^{\frac{1-\alpha}{1-\epsilon}}. \tag{3.61}$$

Equation (61) demonstrates two important properties of this economy. First, prices do not depend on the level of capital. While the economy uses all three productive processes, capital and labor migrate across sectors keeping prices fixed. Second, Θ_t has an ambiguous effect on the price. When capital intensity in the traditional sector, α, is less than the capital intensity of labor-based production in the robotic sector, an increase in Θ_t lowers prices and vice-versa. This is because the increase in robotic productivity draws capital away from investment in both types of machines, and that reduces output of the more machine intensive sector more. A larger reduction in output requires a change in relative prices. As it is intuitive that capital should be more important in the production of the automatable good, we take this to be the standard case.

To better understand how α influences the impact of a change in robot productivity, consider $\alpha = 0$. Also, take $L_t = 1$ in all periods.

The first order condition for the non-automatable good reduces to

$$p_t = \frac{w_t}{D_{Y,t}}. \tag{3.62}$$

Therefore the price will be a function of the wage, which can be thought of as being set in the X sector. In the X sector, an increase in robotic productivity will redistribute capital investment from machines to robots. Because this reduces the marginal productivity of labor while leaving the price of X unchanged, wages must decrease.

Taking the limit of the price equation as $\alpha \to 0$ yields

$$p_t = \Theta_t^{\frac{-\epsilon}{1-\epsilon}} \frac{1}{D_{Y,t}} [\frac{(1-\epsilon)}{\epsilon}][\epsilon D_{X,t}]^{\frac{1}{1-\epsilon}}. \tag{3.63}$$

Prices and wages are both decreasing in Θ.

Returning to the general case, with α and L_t free parameters, the wage is

$$w_t = p_t(1-\alpha)D_{Y,t}[\frac{M_{t,y}}{L_{t,y}}]^{\alpha}, \tag{3.64}$$

which can be rewritten as

$$w_t = p_t(1-\alpha)D_{Y,t}[\frac{\alpha(1-\epsilon)}{\epsilon(1-\alpha)}]^{\alpha}[\frac{\epsilon D_{X,t}}{\Theta_t}]^{\frac{\alpha}{1-\epsilon}}. \tag{3.65}$$

The wage is not a function of capital either. This means that in the period after a change in Θ the economy will jump to its new steady state.

Explicitly,

$$K_{t+1} = C_1[\frac{1}{\Theta_t}]^{\frac{\epsilon}{1-\epsilon}}, \tag{3.66}$$

where

$$C_1 = \frac{(1-\phi)(1-\epsilon)}{\epsilon}(\epsilon D_{X,t})^{\frac{1}{1-\epsilon}}.$$

Note that wages and future capital are decreasing in Θ_t.

Plugging wages and interest rates into the utility function yields an indirect utility function in terms of parameters

$$U_{1,t}(\Theta) = \tilde{C} - [\frac{\epsilon + \phi(1-\beta)(\alpha-\epsilon)}{1-\epsilon}]\ln\Theta_t + (1-\phi)[1 - \frac{(1-\beta)(\alpha-\epsilon)}{1-\epsilon}]\ln\Theta_{t+1}, \tag{3.67}$$

where $\tilde{C}^{30}$ is a function of parameters other than robotic productivity. The utility of the young is always decreasing in today's robotic productivity, while the total effect of robotic productivity is ambiguous.

The long-run welfare impact of a permanent increase in Θ will be negative if

$$(1-\phi) < \frac{(1-\beta)\alpha}{1-\epsilon} + \frac{\epsilon\beta}{1-\epsilon}. \tag{3.68}$$

The impact of increased robotic productivity will be positive if the discount factor is low enough. When labor-based production of the robotic good is more capital intensive, robotic productivity changes will tend to be more damaging to welfare as more labor will be forced out of robotic production and into lower marginal product tasks. Similarly, when the capital share of production in the Y sector is small, output of the non-automatable good is more resistant to reallocation of investment, and the threshold for immiserization is higher.

Using the same logic as in the one-sector model, a government transfer can turn an increase in robotic productivity into a long-term welfare improvement. Government transfers of the type discussed above will not change the pre-transfer wage, and therefore must increase capital stocks that are linear in post-transfer wage. An increase in capital stocks must increase output. If the transfer is set so as to bring w_t^N after innovation equal to w_t before the innovation, no profits necessitates that the old consume more because total output has increased.

An economy can evolve from this case to either the no-robot or only robot case in one of two ways. Most simply, if a parameter such as Θ were to change then either equation (56) or (57) may bind. More subtly, if $K_{t+1}(\Theta_t)$ is large or small enough then an economy in the mixed case at (K_t, Θ_t) will immediately jump to one of the other cases. This can lead to permanent cycles in the economy if in the only-robot case the economy contracts.

Case 3: Only Robots Produce the Automatable Good

In the final case of the economy, robotic productivity is so high that no machines or labor are used in the automatable sector. Intuitively, when labor is relatively scarce firms should substitute for it as much as they can.

Without transfers, an economy in this case is set on a path of permanent growth or temporary contraction similar to an AK model. The potential for permanent growth arises from the fact that the rise of Θ raises the relative price of Y, which can in turn raise the wage, the level of saving, and investment. At the initial price level, a rise in Θ shifts capital to robotic investment, thereby raising the output of X and lowering the output of Y. Yet demand for the traditional good rises because retirees boost their overall demand, of which traditional consumption is a fixed share. This results in excess demand for the traditional good, requiring a rise in prices to clear the market. As the price rises, so too can wages. The effect on wages will be the net of the increase in price and the decrease in the marginal productivity of labor due to capital flight. If there is an increase in the wage, this causes a rise in national saving and thereby a rise in investment. With more saving there is also more demand for the traditional good, which is limited by the fixed supply of labor. An ongoing cycle of growth will continue despite the fixed input of labor.

Robots will necessarily be utilized, so $1 + r_t = m_t = \Theta_t$. The non-negativity constraint for inputs to machine production of the automatable good binds, so $L_{Y,t} = L_t$ and $M_{X,t} = K_t - R_t$. Assume that there are no government transfers. Then rearranging first order conditions yields

$$w_t L_t = M_t \frac{\Theta_t(1-\alpha)}{\alpha}. \tag{3.69}$$

Combining the robotic production function with the robotic market clearing condition yields

$$\Theta_t R_t = x_{1,t} + x_{2,t} + K_{t+1}, \tag{3.70}$$

and substituting household demands gives,

$$\Theta_t[K_t - M_t] = (1-\phi)w_t L_t + \phi\beta w_t L_t + \beta\Theta_t K_t, \tag{3.71}$$

which may be reduced to

$$M_t = \frac{\alpha(1-\beta)}{1-(1-\alpha)\phi(1-\beta)} K_t, \tag{3.72}$$

giving a law of motion for capital

$$K_{t+1} = \frac{(1-\beta)(1-\phi)(1-\alpha)}{1-(1-\alpha)\phi(1-\beta)} \Theta_t K_t. \tag{3.73}$$

Thus, capital evolves linearly across periods. When the term multiplying K_t is less than 1, the economy will contract. When greater than 1, it will grow indefinitely. Note that this term is not dependent on D_Y but it is increasing in robotic productivity. This is because increases in the price of the traditional good guarantee that a stable fraction of the robotics output is devoted to saving for more robots. Increased robotic productivity may lead the world from poverty into permanent growth but increasing traditional productivity will have no long-run effect on growth rates. If total factor productivity in the traditional sector were to increase, its price would drop by precisely the amount necessary to keep the wage constant. The multiplier is also increasing in the saving rate $1-\phi$. Government interventions to increase saving have the potential to move the economy from steady contraction to unconstrained growth.

When the economy is on the contraction side of knife-edge growth, savings and capital will decrease until (57) no longer holds. If the case that the economy moves into then leads to an increase in capital stocks, the economy may exhibit an endogenous business cycle of growth and contraction indefinitely. An example is given in the simulations below.

It is easy to see that the knife-edge growth case will have a positive long-run effect on utility. The knife edge growth case is growing precisely because wages are increasing, and the increase in capital indicates that the old have higher incomes as well.

To better understand the difference between the one-sector model and this phase of the two-sector model, consider $\alpha = 0$. This is the case where no machines are used in producing Y. Then the two production functions are

$$X_t = \Theta_t R_t, \tag{3.74}$$

$$Y_t = D_{Y,t} L_t, \tag{3.75}$$

and, further assuming $L_t = 1 \; \forall t$,

$$Y_t = D_{Y,t}. \tag{3.76}$$

First, consider what happens when the two goods are perfect substitutes as in the one-sector model. The wage w_t is simply $D_{Y,t}$, and the economy immediately reaches a steady state with

$$\overline{R} = (1 - \phi) D_{Y,t}, \tag{3.77}$$

and

$$\overline{X} = \Theta_t (1 - \phi) D_{Y,t}. \tag{3.78}$$

There is no growth. A rise in Θ increases lifetime utility for all generations by raising the return on saving. There is no adverse wage effect, as there is no capital flight to reduce the productivity of labor.

Now consider the very different outcome in the two-sector, only-robots case. The wage w_t now equals $p_t D_{Y,t}$. Saving is $S_t = (1-\phi)p_t D_{Y,t}$. Total demand for X_t is

$$X_t = \phi\beta p_t D_{Y,t} + \Theta_t \beta R_t + (1-\phi)p_t D_{Y,t}. \tag{3.79}$$

We therefore can find p_t by equating the supply and demand for X_t. Specifically,

$$p_t = \Theta_t(1-\beta)R_t/[\phi\beta D_{Y,t} + (1-\phi)D_{Y,t}]. \tag{3.80}$$

Using the relationship $R_{t+1} = S_t = (1-\phi)p_t D_{Y,t}$, we find a difference equation in R_t,

$$R_{t+1} = \Theta_t(1-\beta)(1-\phi)R_t/[\phi\beta + (1-\phi)]. \tag{3.81}$$

In both this and the more general case, a fixed share of robotic output is devoted to investment.

Returning to the general model, when only robots are used for producing the automatable good, transfers still have the potential to increase long-run welfare. For a fixed transfer G satisfying

$$-\frac{[1-(1-\beta)\phi]\left(\frac{1-\alpha}{\alpha}\right)+1}{\left(\frac{1-\alpha}{\alpha}\right)[\theta(1-\beta)+\beta G]} < 1-\phi < \frac{[1-(1-\beta)\phi]\left(\frac{1-\alpha}{\alpha}\right)+1}{\left(\frac{1-\alpha}{\alpha}\right)[\theta(1-\beta)+\beta G]}, \tag{3.82}$$

the economy will converge to a steady state. Otherwise the economy will experience AK growth/contraction. This means that the economy has the potential to be shunted out of contraction by a transfer.

When (82) holds, capital stocks converge to

$$K^{ss} = \frac{(1-\phi)G}{1 - \frac{(1-\phi)(\frac{1-\alpha}{\alpha})}{[(1-(1-\beta)\phi)\left(\frac{1-\alpha}{\alpha}\right)+1]}}. \tag{3.83}$$

3.6 Simulating The Two-Sector Model

In figures 1 and 2 we display the path of an economy with parameters given in table 1. These figures demonstrate how a government transfer program can turn a potentially utility-reducing rise in robotic productivity into a welfare improvement for all generations. In this simulation in all periods producers use both robots and machines in the production of the automatable good. From periods zero through four, the economy is in its steady state. In period five Θ increases from 1.25 to 2. Without transfers, this leads to a temporary boom. High savings carried over from period four are combined with the new technology and create high levels of output, most of which accrue to the old due to the decrease in labor's share of income. From period five on, citizens suffer as a result of the increase in productivity. Welfare falls far below the dashed line indicating the no-innovation utility path.

Introducing a transfer changes the outlook for the economy. Capital income taxes, set at rate of about 70 percent, fund a transfer that keeps the net income of the young constant. This keeps capital stocks constant while prices are unchanged. Relatively higher capital stocks outweigh the impact of the tax and increase the net income of the old. Every generation benefits from the combination of technological change and transfers.

Figures 3 and 4 investigate a more complex case. The economy begins in period zero just below the steady state level of capital given initial Θ. For the initial level of Θ, in the steady state robots are too inefficient to be used. The economy is in case one. In this second pair of simulations, we investigate the consequences of robotic productivity innovations occurring every five periods beginning in period five.

Consider the consequences for the economy without transfers. After the first innovation, the economy moves into case two (mixed production of the automatable good). Welfare hits a local maximum as the old receive large retirement incomes from the interest rate increase. But the increase in robotic investment lowers wages. In the period after the innovation utility settles at a new lower level due to lower wages and capital. In period ten another innovation occurs, but the economy remains in the second case. Another local maximum in welfare follows, before welfare falls even further.

In period fifteen innovators strike again. In the period of the third innovation, there is a third local maximum in the utility of the old. The economy has moved into the third case where only robots are used in production. However, the multiplier on K_t in (73) is less than one, and the economy immediately begins to contract because of low wages. Wages are low because the negative wage effect of losing an opportunity for employment in the automatable sector dominates the positive effect of increases in non-automatable good prices (which are in turn due to their increased relative scarcity).

After a single period capital has dissipated enough that case two binds again. In period sixteen, although capital is scarcer, wages are higher than in the previous period because workers are being used to produce the automatable good again. High wages increase savings and future capital, moving the economy into the third case. Periods where only robots are used have low wages, reducing savings. The economy is on the bad side of knife-edge AK growth. In subsequent periods, capital stocks are low enough that the second case binds. Laborers find work again in the automatable sector and wages increase. Capital stocks and the economy expand, moving the economy back into the third case. These oscillations have important welfare implications as those retired in periods where robots are used and working when case two binds have high wages when young and high retirement incomes when old. Those unlucky to be born in the other period of the business cycle are worse off. Cycles of more than one period are possible, although the economy will not spend more than one period in case two per cycle.

The economy would oscillate indefinitely were it not for a final innovation in period twenty. This moves the economy on to the good side of knife-edge growth. The positive effect on wages of high non-automatable good prices dominates. The economy grows indefinitely with benefits for all future generations. For a wide variety of parameterizations, a noisy U-shaped path of utility as Θ increases will occur. In early periods robotic productivity leads to immiserization, but eventually robots are so super-productive that indefinite growth must kick in.

The path of welfare can be improved through government transfers. Here is displayed one of a large set of transfer schedules that turn the series of innovations into an improvement for all generations over robots being banned. Curiously, the transfer improves welfare by depressing labor's share of income even further in some periods. This is due to greater investment, which requires the output of the more capital intensive X sector and leads to higher future capital income. Note also how in the periods 15 through 19 how the economy with transfers fails to undergo cycles of growth and contraction but rather approaches the asymptotic level of capital derived in (83).

Figure 5 shows the long-run impact of a robotic productivity improvement on an economy in case two. Unsurprisingly, when the saving rate is high the increase in robotic technology (and hence interest rates) is more likely beneficial. When capital's share of income in production of the traditional good is higher, robotic innovations are more likely to immiserize by crowding out investment in a more

Table 3.1: Parameters for First Simulation

Model Parameter	Role	Value
ϵ	X Sector Capital Input Share Param.	0.33
α	Y Sector Capital Input Share Param.	0.33
Θ	Robot Productivity	Varies
$1-\phi$	Youth Saving Rate	0.3
L	Labor Supply	1
G	Transfer to Young	Varies
β	X Sector Consumption Share	0.5
K_0	Initial Capital	.104
$D_{X,t}$	TFP in X Sector	1
D_Y	TFP in Y Sector	1

Note:This table gives parameter values for the first pair of illustrations of the model.

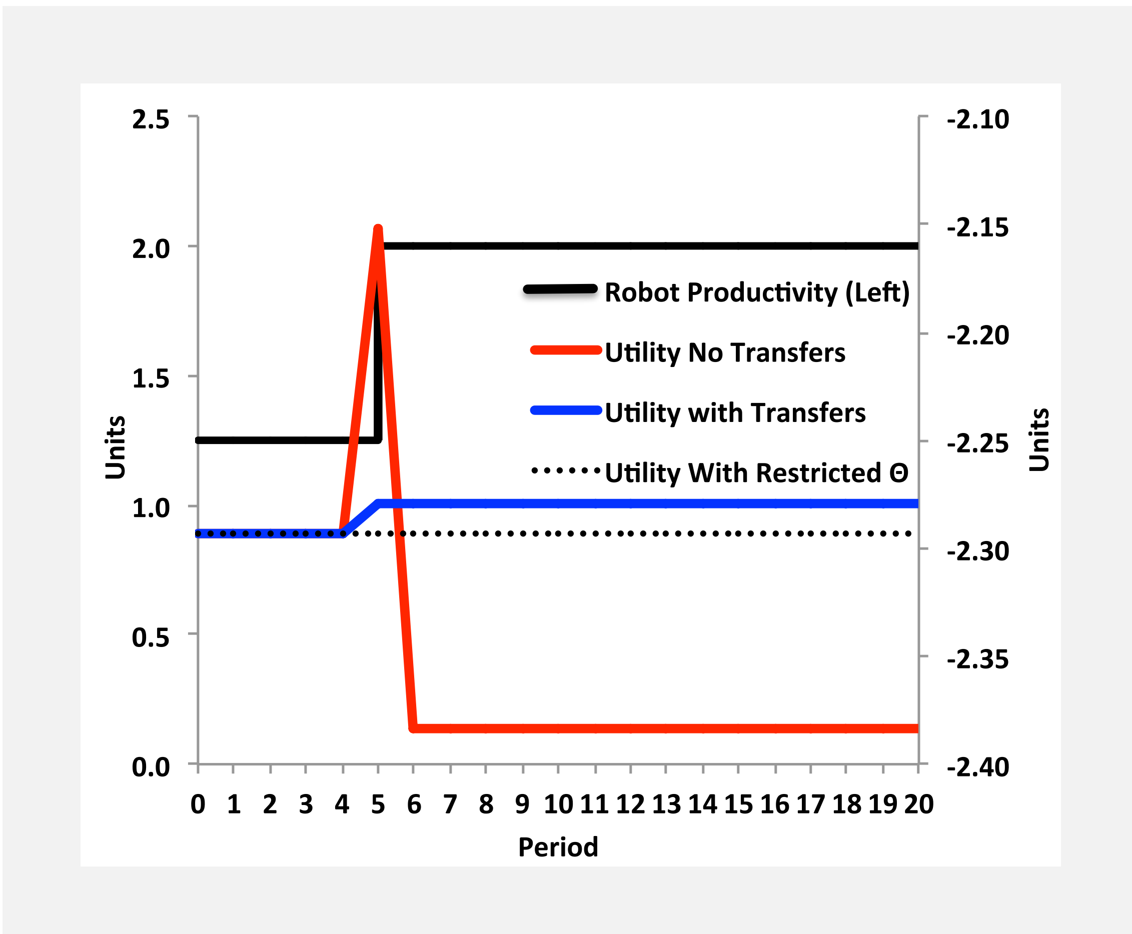
important complement to labor.

3.7 Conclusion

The rise of the robots is already creating major disruption in labor markets, essentially turning production processes more capital intensive. When robots are close substitutes for production by labor and machinery, the demand for labor is likely to decline, threatening a decline of wages, saving, and economic well-being of current and future generations. We have qualified that intuition, however, in two important ways. First, government redistribution can ensure that a pure productivity improvement raises well-being of all generations. In the example shown in the paper, government taxes the capital owned by retirees and distributing the proceeds to young workers. Second, to the extent that workers produce outputs that are imperfect substitutes of the outputs of robots, workers will experience a rise in demand for their products, and this can result in a virtuous circle of rising wages, savings, and production, producing the open-ended constant growth of an AK model.

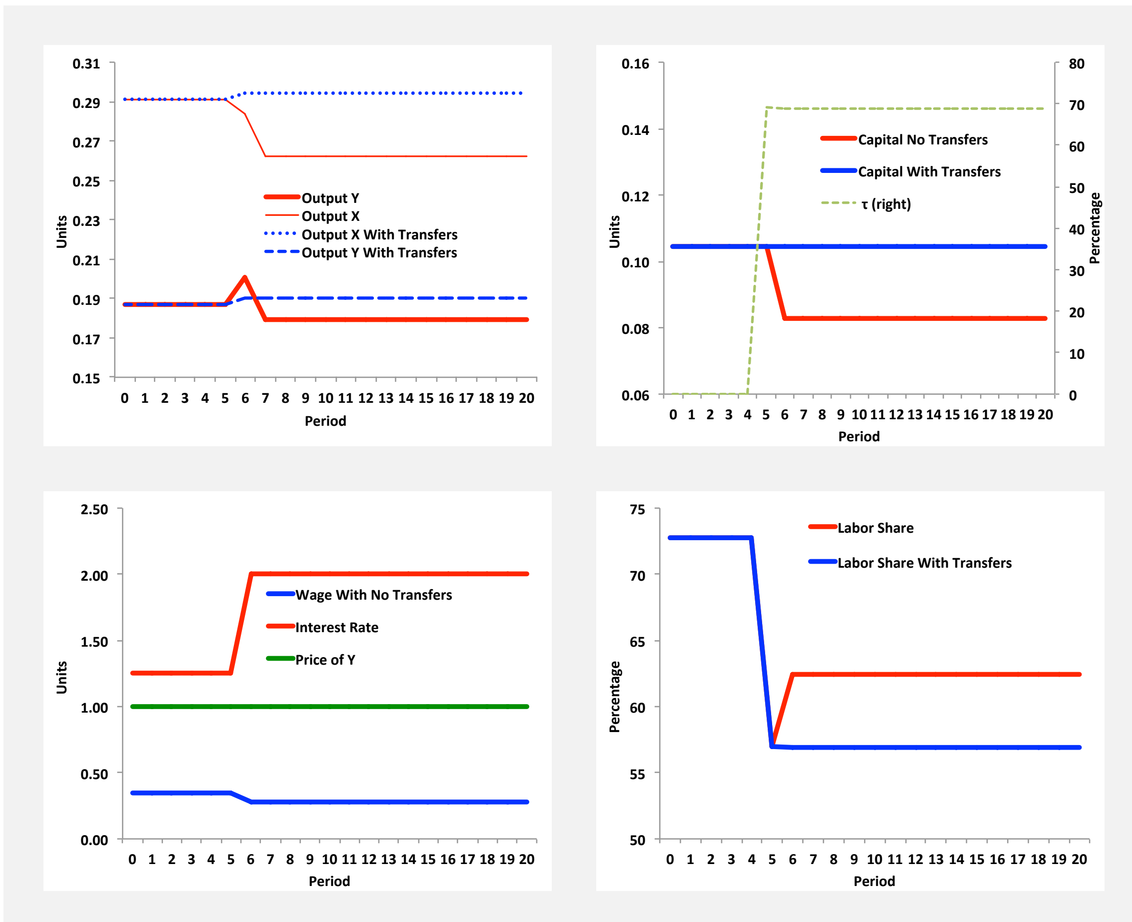
3.8 Annex: Tables and Charts

Figure 3·1: Simulation 1: Welfare



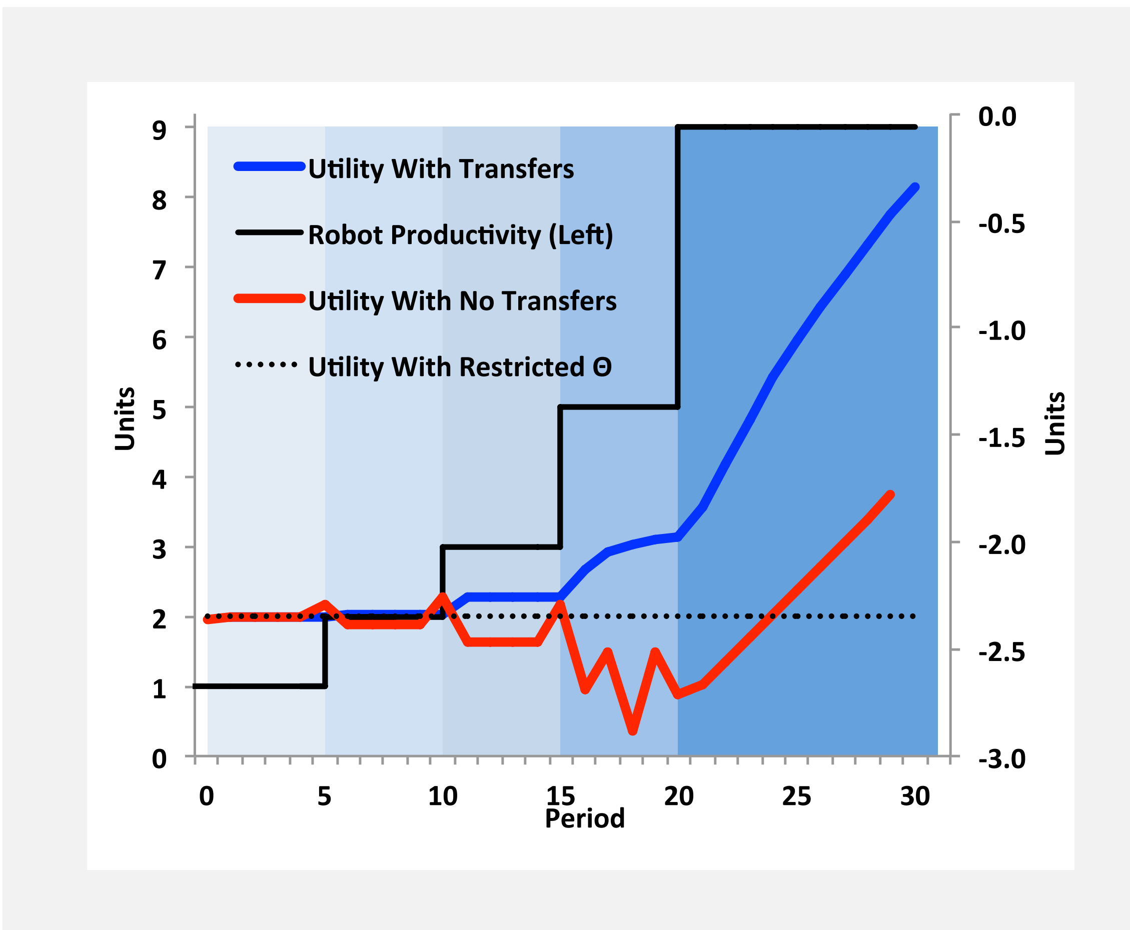
Note: Utility and Θ paths for an economy with and without transfers before and after an increase in Θ. Welfare is lifetime utility of those retired in a period. Parameter values are as in Table 1.

Figure 3·2: Simulation 1: Other Economic Variables



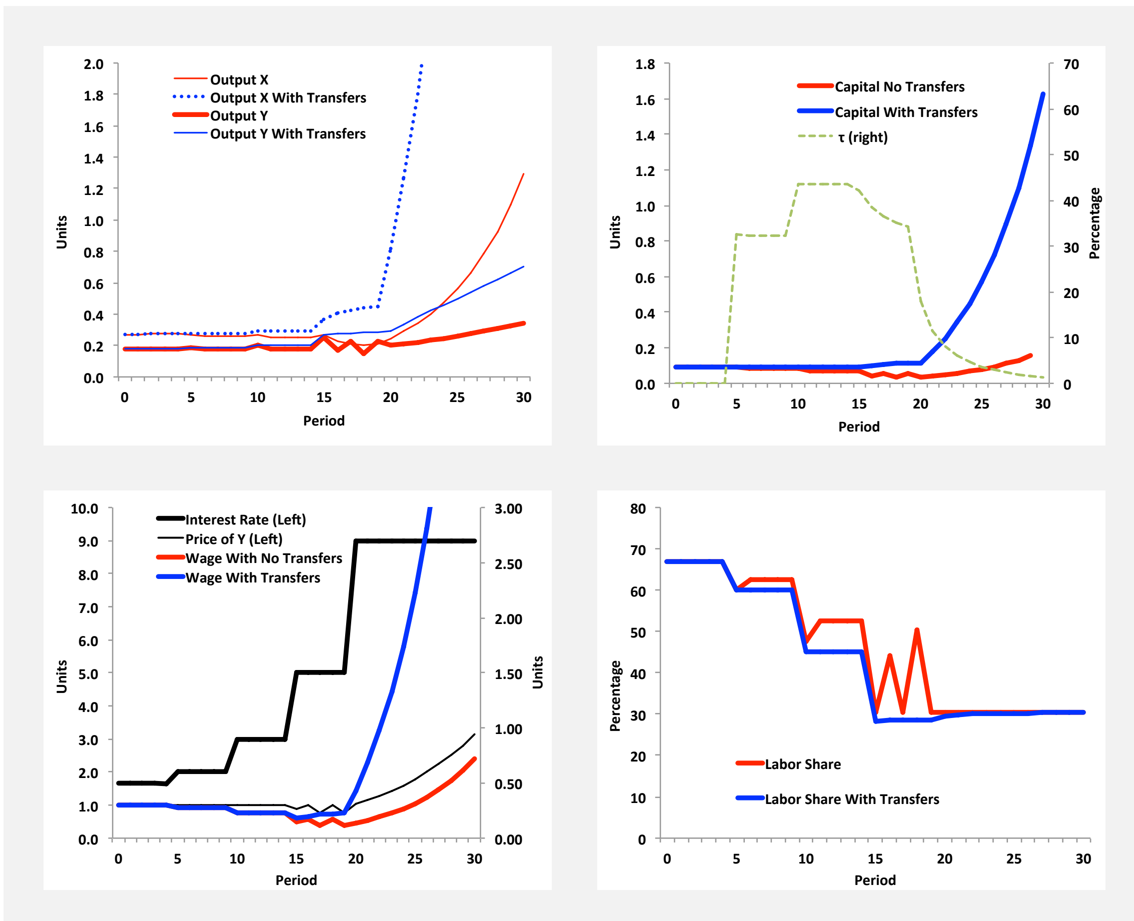
Note: Economic variable paths for an economy with and without transfers before and after an increase in Θ. Prices are identical in the with and without transfer cases; the before transfer wage is displayed. Outputs are given in terms of units of output and do not take into account price. Labor shares of income are market shares, and do not include taxes and transfers in either case. Parameter values are as in Table 1.

Figure 3·3: Simulation 2: Welfare



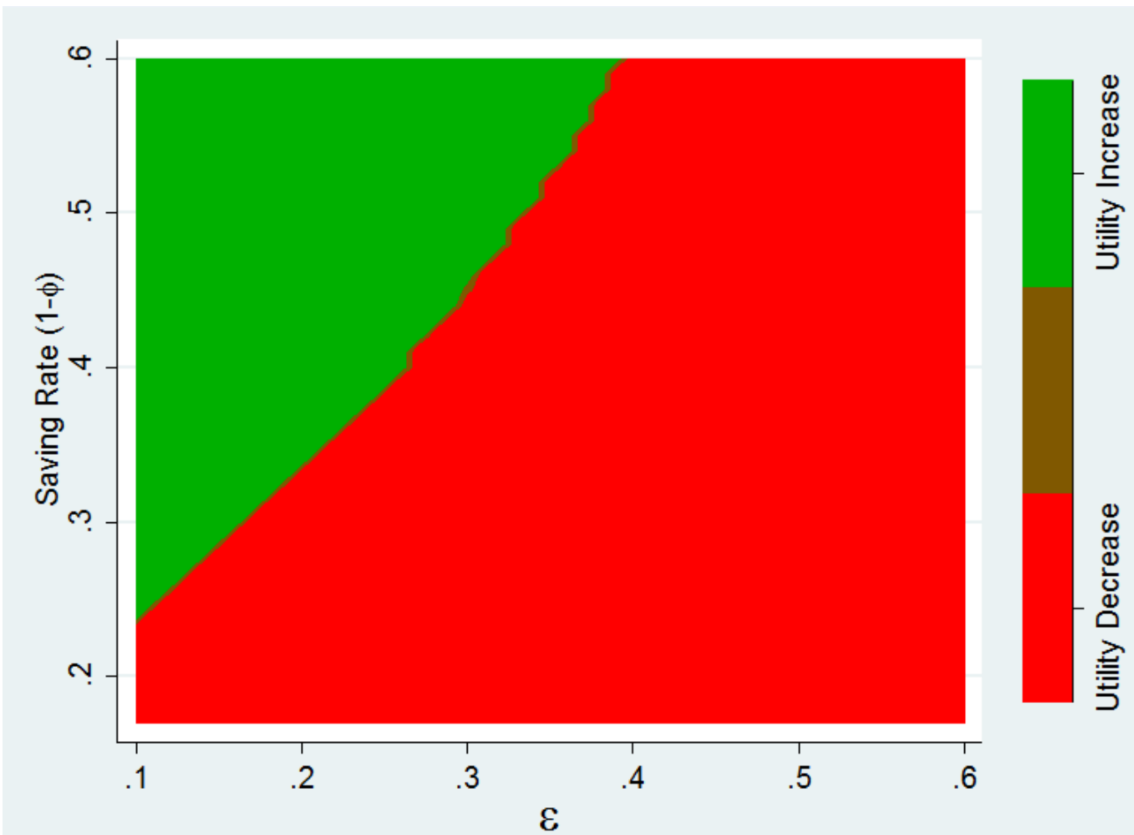
Note: Utility paths for an economy with and without transfers before and after several increases in Θ. Welfare is lifetime utility of those retired in a period. Parameter values are as in Table 2.

Figure 3·4: Simulation 2: Other Economic Variables



Note: Economic variable paths for an economy with and without transfers before and after several increases in Θ. 'Wage With Transfers' displays the market wage in the transfer case and does not include transfer income. Outputs are given in terms of units of output and do not take into account price. Labor shares of income are market shares, and do not include taxes and transfers in either case. Labor Parameter values are as in Table 2.

Figure 3·5: Role of Parameters in Determining the Welfare Impact of $\Delta\Theta$ in the Mixed Case



Note: The green zone indicates indicates the range of parameter values such that an increase in robotic productivity has a positive long-run impact on utility; for the red zone the opposite holds. The economy begins in the steady state with $\Theta = 1.25$ and is compared to the steady state with robotic productivity slightly elevated. Parameters not on axes are as in Table 1.

Table 3.2: Parameters for Second Simulation

Model Parameter	Role	Value
ϵ	X Sector Capital Input Share Param.	0.33
α	Y Sector Capital Input Share Param.	0.33
Θ	Robot Productivity	Varies
$1-\phi$	Youth Saving Rate	0.3
L	Labor Supply	1
G	Transfer to Young	Varies
β	X Sector Consumption Share	0.5
K_0	Initial Capital	.29
D_X	TFP in X Sector	1
D_Y	TFP in Y Sector	1

Note: This table gives parameter values for the second pair of illustrations of the model.

Chapter 4

Can Russia Survive Economic Sanctions?[31]

4.1 Introduction

In March 2014, following the Russian annexation of Crimea, the United States, Canada, EU, and several other nations levied a series of sanctions on Russian businesses and individuals. The goal of these sanctions were to compel Russia to end its interventions in Ukraine. Russia responded with counter-sanctions, including a ban on food imports from these regions. Further targeted sanctions were imposed by the US on Russia in late 2016, following accusations of Russian meddling in US elections. While leaders on both sides have called for economic de-escalation, Russian revisionism and the incoming Trump administration's unpredictability make a wide range of developments possible.

Motivated by these events, this paper develops a model of the most severe sanctions possible. Sanctions so severe that they force Russia into a long-term state of autarky. While not the most likely outcome, understanding what would happen in this situation is critical. For example, calculating the welfare impact of this possibility puts an upper bound on the painfulness of sanctions. More subtly, in a game of brinkmanship, knowing each sides' utility from the worst possible outcome is critical to predicting future outcomes, even if the worst possible outcome is rarely arrived at. This study also provides insight into the welfare consequences of extreme sanctions in general, and the role of different policy responses to those sanctions.

Despite a large empirical and theoretical literature on the impact and effectiveness of sanctions, no previous paper studies the long-term impact of sustained sanctions in a setting with many agents and an active fiscal policy. The model we develop is based on the computable, general equilibrium models pioneered in Auerbach and Kotlikoff (1987), and most directly on a descendant model discussed in Benzell et. al. (2016). The model is a large-scale, six-region, life-cycle model, with every country having ninety generations and two income classes of rational agents. Countries trade, produce, invest, and go into debt. Our model's primitives are simple, but we incorporate features that make it more realistic than classic trade models. We assess the impact of various types of sanction regimes on different generations and types of agents within the sanctioned country. The model takes into account the interconnected demographic and fiscal transitions of the six major economies in the world -China, E.U., U.S., Japan (plus Korea), India, and Russia. When Russia is forced into autarky, it can no longer borrow from, or invest its assets abroad. In some scenarios we also assume that its fossil fuel stockpiles lose a percentage of their value. This model is the appropriate format for measuring the long term consequences of autarky. The model does not have a focus on trade in heterogeneous products. Rather, it focuses on intertemporal trade, which is trade's most important aspect in the long run. By intertemporal trade, we mean foreign direct investments or loans from one nation to another. These investments are made in order to receive profits and rents in the future. While missing intermediate inputs or foreign delicacies can be painful in the short term, in the medium term a country at Russia's stage of technological development can re-specialize their industry mix. In some scenarios, we model this temporary loss from the need to re-specialize as a productivity shock.

We investigate several different scenarios. In the most benign version of autarky for Russia, one in which the energy industry is unaffected and foreign capital is seized by the government, current generations of the elderly see their lifetime welfare reduced by about twenty percent, while generations born today are about four percent better off. In one of the most severe scenarios, in which the energy sector is severely impacted and capital flees, in the short run GDP decreases 40%. Even after 20 years, GDP remains 30% below its baseline path. This negative impact on output reduces welfare for all cohorts born from 1940 through 2040. Autarky has a heterogeneous impact on different generations of Russians, which varies based on the details of the scenario. In scenarios where the Russian capital stock is severely reduced, the young tend to suffer relatively more, as the old recoup some of their losses from higher interest rates.

Sanctions may also hurt Russia through the productivity channel. This could be due to the need to re-specialize mentioned above. Another related is that spillovers that contribute to improve labor productivity, such as innovation or know-how diffusion, vanish when sanctions lead to autarky. In normal times, trade allows for multiple forms of spillovers to reach trading partners. In (Kiriyama, 2012), the OECD summarizes how imports and foreign direct investment (FDI) as well as trade in technology serve as channels of technology diffusion that improve labor productivity in the long run. A key element in their findings is that trade can affect productivity as it serves as a learning opportunity for workers and gives incentives for implementation of innovative activities. Our third scenario captures this through a productivity shock. The impact of this is to further reduce welfare for generations born from 1940 through 2040.

Can Russia implement policies to avoid the long lasting negative effects? Our model says it can't, although it can mitigate the damage. If Russia enforces capital controls (i.e. seizing all Russian assets owned by foreigners), Russia's capital stock will be initially unharmed. Sanctions will, nonetheless, reduce gains from trade, causing GDP to drop 7% in the medium term relative to its performance in the baseline case. Older generations will suffer the most as they cannot spend their savings as they would have in absence of sanctions. Welfare losses also affect those born in 2020, although to a lesser extent.

The remainder of the paper is organized as follows. Section II conducts a review of the relevant literature. Section III is devoted to specify the model and assumptions. Section IV presents results. Section V concludes.

4.2 Literature Review

Economic sanctions are a key tool of international politics. They serve as punishments for nations that violate international or bilateral agreements. They are ostensibly imposed to change the behavior of policy makers. This could be by weakening political power structures or inducing social consciousness. In the last 20 years, the world has seen a proliferation of sanctions. The U.N. Security Council has imposed sanctions in Angola (1993, 1997, and 1998), Rwanda (1994), Sudan (1996), Sierra Leone (1997 and 2000), Afghanistan (1999), Ethiopia and Eritrea (2000), and more recently in Iran and North Korea.

Sanctions involve boycotts, embargoes, and financial restrictions. A boycott is a reduction or complete restriction of imports of one or more goods from the target country. Boycotts aim to reduce the target's foreign earnings and therefore its ability to purchase goods. They can target industries that are seen as aligned to the regime, while leaving others untouched. The effectiveness of boycotts, however, is limited. The target country may be able to find alternative markets or arrange triangular purchases to circumvent controls. Embargoes, on the other hand, restrict trade with the target country.

Finally, financial sanctions restrict or suspend lending and investing by penalizing any institution that has a financial transaction with the sanctioned country.

Sanctions are meaningful as long as they inflict pressure on policy makers in the target country. Given that sanctions inhibit access to foreign goods and services, agents within the country are forced to turn to their government for help. The government may be able to weather the crisis by making targeted cuts to the state budget while providing fiscal stimulus to boost investment and consumption.

The scenario we consider in this paper is extreme. However, there is at least one example of a country forced into nearly complete long-term autarky. Noland (2004) discusses the history, causes, and consequences of North Korea's isolation on its nuclear program (the source of international opprobrium) and the welfare of its common people. During the Cold War era North Korea adopted a policy of Juche, or self reliance, never joining the Soviet economic block (COMECON) and deliberately de-syncing its 5-year plans with Russia's. After the fall of the Soviet Union their isolation became even more perfect. Despite this, North Korea has managed to maintain an impressive military, even developing nuclear weapons, albeit at devastating costs to normal individuals. While pushing Russia into long term autarky is an extreme scenario, it has a precedent just next door.

Nations' repeated use of sanctions as a tool for coercion has been studied in several economic papers. This research explores the links between sanctions' success and factors such as the political cost of sanctions to the sender state and/or target state, dyadic political relationships between senders and targets, the domestic characteristics of the sender and/or target, the matching of issue salience with the level of sanctions, and international cooperation ((Dashti-Gibson et al., 1997); (Kirshner, 1997); (Morgan and Schwebach, 1997);(Drezner, 1999); (Hart et al., 2000); (Cortright and Lopez, 2002); (Nooruddin, 2002); (Brooks, 2002); (Jing et al., 2003);

(Lacy and Niou, 2004); (Allen, 2005); (McGillivray and Stam, 2004); (Lektzian and Souva, 2003), (Lektzian and Souva, 2007)).

Much of this literature is skeptical that sanctions have a large effect. However, these studies have focused on shorter term sanctions regimes. They leave aside important general equilibrium effects resulting from more stringent or longer term sanctions. It makes sense, therefore, to study under what particular circumstances economic sanctions do, in fact, have a profound impact.

The early literature associated with sanctions studies them in terms of welfare losses due to the limited trade. (Frey, 1984)[32] uses a simple two-commodity small open economy model to characterize the negative impact of trade restrictions. The results show the importance of the elasticities of the target nation's supply and demand curves. The more rigid the production structure of an economy, the larger its welfare loss. (Gray, 1986) argue that the only way to inflict a severe economic punishment is to be able to withhold imports of goods in the target country. In fact, the author finds that sanctions are more damaging to the target country if they are imposed on imports of *non-competitive* products. (Black and Cooper, 1987) also study welfare effects in a general equilibrium framework. They illustrate how economic sanctions may affect the level and distribution of welfare in a target country. Welfare loss due to sanctions varies with price elasticities of the domestic supply and demand for exports and imports. Similar to our model, they assume that sanctions are severe enough to lead to a state of autarky. However, the static nature of their setup contrasts with our life-cycle structure which better captures the intergenerational impact of trade and allows for a better understanding of welfare and investment flows.

While the aforementioned studies assume that effective sanctions will lead to a state of autarky, their analysis is limited to those cases where such a movement results in welfare losses. Thus, they fail to consider the possibility that autarky may be preferable to free trade; Reasons for this include significant domestic internal and external economies arising from the termination of trade ((Singer, 1950); (Myint, 1963)), and the existence of monopolistic markets ((Haberler, 1988)) or factor price distortions ((Bhagwati and Ramaswami, 1963); (Pattanaik, 1970); (Hazari, 1978)) may drive a significant wedge between a commodity price and its marginal social cost or benefit.

A more realistic approach is one that considers the actions that a country may take in response to sanctions.(Bhagwati and Srinivasan, 1976) and (Tolley and Wilman, 1977) study policy actions that could make a country more resilient to sanctions. (Bhagwati and Srinivasan, 1976) develop a stochastic, two-period, two-goods model with adjustment costs and study trade disruptions. In their model, a country in danger of an export embargo can mitigate welfare losses by imposing a tariff. The optimal tariff is proportional to the expected loss in welfare before the sanction takes place. Similarly, (Tolley and Wilman, 1977) focus on tariff policies to prepare for a probable trade disruption. They use a partial equilibrium framework where countries optimally choose consumption goods to maximize welfare. The optimal tariff is proportional to foreign dependence, inversely proportional to elasticity of external embargo loss, and incremental with the embargo probability. Our investigation is complementary to this literature as we study policy responses to sanctions with a life-cycle structure. Our model is flexible enough to determine welfare effects if the country allows for capital flight or imposes restrictions, namely seizing foreign assets and defaulting on debt. Our results suggest that as trade termination materializes, welfare declines for current and some future generations. This condition holds even if the target country only defaults on debt held by foreigners.

More recently, research has focused on the determinants of a nation's endurance of economic sanctions. (Bergeijk, 1989) pioneers this literature by empirically identifying a number of variables that determine a country's ability to withdstand economic sanctions.[33] The probability that an economic sanction succeeds is higher when pre-sanction trade linkages are larger. The target country's political situation and the length of the sanction period are also important factors to consider. (Dizaji and van Bergeijk, 2013) investigate why success predominantly occurs in the early phase of a sanction episode. Patterns of success and duration of sanctions are related to the target's and sender's institutional characteristics and the changes therein ((Bolks and Al-Sowayel, 2000); (McGillivray and Stam, 2004)), to commitment strategies ((Dorussen and Mo, 2001)), and to Bayesian learning ((Van Bergeijk and Van Marrewijk, 1995)).

Moving beyond the macroeconomic models, according to (Losman and Richardson, 1980), (Lindsay, 1986), and (Kaempfer and Lowenberg, 1986), sanctions often have effects opposite to those desired by the sanctioners. (Scolnick, 1988) provides anecdotal evidence to support the fact that even when sanctions do have substantial economic effects, they may be politically counterproductive. This has been termed the "rally around the flag" effect ((Willett and Jalalighajar, 1983)). In our model these situation may arise if certain conditions are met by the sanctioned country, among them being a net lender and carrying trade surpluses.

Unlike the above, (Kaempfer and Lowenberg, 1988);(Kaempfer and Lowenberg, 1999) take a public choice approach. They show that sanctions that have weak economic effects can still ignite policy changes by signaling cooperation or disapproval to the target country's interest groups. (Marinov, 2005) develops a theory that links economic activity to the likelihood that the target's leadership will survive. Growth slowdowns are associated with higher political turnover. Sanctions may either help to replace the target's government or encourage a bargaining process, making the target's leadership more willing to compromise due to increasing political costs of not complying (that is, a higher likelihood of government turnover). While we acknowledge the importance of these perspectives, we limit ourselves to the macroeconomic consequences of sanctions.

In contrast to most of the literature on sanctions, we focus on the effect of trade restrictions on medium and long term investment flows. In other words, inter-temporal trade. In particular, a nation's capital stock and worker productivity will suffer if the prevention of foreign direct investment reduces overall investment. On the other hand, if the sanctioning parties are net capital importers, investment barriers may help workers in the sanctioned country by making sure savings are invested domestically. Chantasasawat et al. (2004) provide evidence that China's demand for FDI does not in fact starve other Asian countries of investment. This is in line with our results, which suggest that cutting off Russia from world investment reduces rather than increases their rate capital accumulation.

Our paper contains many of the above features but contributes to the literature by introducing a much more realistic setting in which sanctions take place. We focus on a single good; however, our model is much more detailed in terms of demographic, pension, and fiscal profiles. Contrary to the literature discussed above,we study sanctions using an intergenerational approach. By including households behavior, firms decisions and a public sector in a robust OLG environment, we can individually investigate in great detail the impact of sanctions on each generation and labor-skill class.

The model employed in this paper is in the tradition of overlapping generations models canonized in Auerbach and Kotlikoff (1987). These models have had great success in answering questions related to demographic transitions and long term fiscal policies. Another approach to these issues are the MSG-Cubed models featured in such papers as McKibbin (2006). These models are also overlapping generations models. They differ from our model in that they allow for irrational behavior by agents. Allowing for these deviations comes at a significant cost, as markets in the model no longer clear in general, and therefore the models cannot be considered truly general equilibrium.

4.3 The Model

The baseline model is an overlapping generations model of the worlds six largest economies. It is based primarily on the model developed in Benzell et. al. (2016). We model the United States (U.S.), the European Union (E.U.), China, Japan plus Korea, India, and Russia. Together, these countries account for more than 65 percent of world GDP.

We begin by describing how our model treats demographics. We then discuss household preferences and the model's supply side. Since Russia's main export is oil, we include it through a simple formulation of the energy sector. Next, we specify the model's fiscal policy and describe the sanction mechanism. Finally, we explain the model's solution algorithm.

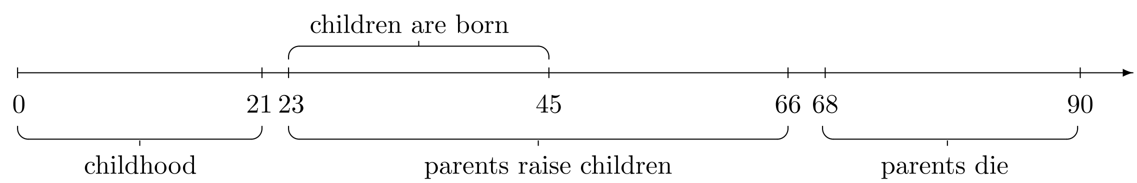
4.3.1 Demographics

Agents in each country live to at most age 90. Therefore, in every year there are 91 generations with living members. As depicted in figure 1, Between ages 0 and 20, agents are non-working children supported by their parents. At age 21, agents enter the labor force and accumulate assets. As in (Kotlikoff et al., 2007), between ages 23 and 45 agents give birth, annually, to children (in fact, to fractions of children). This approach generates a realistic distribution of births and population by age. It precludes having to explicitly incorporate marriage in the model, with different couples producing different numbers (including zero) of children at specific child-bearing ages. An agent's first-born children (those born when the agent is 23) leave home after 21 years when the agent is age 44. The last-born (those born when an agent is 45) leave when the agent is 66.

No one dies prior to age 68, an assumption that simplifies our modeling of bequests. It ensures that children always outlive their parents. If a parent reaches age 90, her oldest children, born when the parent was 23, will be 67. For India, where infant mortality is strikingly high, we also incorporate a small rate of infant mortality. This rate is .0093 in 2013 and it declines linearly to .0003 in 2058. After that date it remains constant. Infant mortality in the other regions is negligible and its inclusion would not materially alter our calibration. Agents die with increasing probability between ages 68 and 90, with certain death at age 90.

Agents accrue no utility from leaving bequests. Hence there are no intentional bequests. Instead, bequests arise due to the model's agents not being fully annuitized (i.e., they die with assets on hand that they intend to spend through the rest of their potential lives).

Figure 4·1: The individual life-cycle



The model also includes annual age-specific immigration. Every year new immigrants in each skill and age group arrive with the same number and age distribution of children and the same level of assets as natives of the identical skill and age. Once they join a native cohort, they experience the same future age-specific fertility and mortality rates as native-born cohort members. Agents of an age-skill group within a country are perfectly homogeneous at all times.

4.3.2 The household sector

The model's preference structure follows that of (Fehr et al., 2013). It is represented by a time-separable, nested, CES utility function. Remaining lifetime utility $U_{a,t,k}$ of an agent age a at time t belonging to skill-class k takes the form:

$$U_{a,t,k} = V_{a,t,k} + H_{a,t,k}, \tag{4.1}$$

where $V_{a,t,k}$ records the agent's utility from her own consumption and leisure and $H_{a,t,k}$ denotes the agent's utility from her children's consumption.The two sub-utility functions are defined by:

$$V_{a,t,k} = \frac{1}{1-\frac{1}{\gamma}} \sum_{i=a}^{90} \left(\frac{1}{1+\delta}\right)^{i-a} P_{a,i,t} \left[c(i,t+i,k)^{1-\frac{1}{\rho}} + \varepsilon \ell(i,t+i,k)^{1-\frac{1}{\rho}}\right]^{\frac{1-\frac{1}{\gamma}}{1-\frac{1}{\rho}}} \tag{4.2}$$

$$H_{a,t,k} = \frac{1}{1-\frac{1}{\gamma}} \sum_{i=a-23}^{22} \left(\frac{1}{1+\delta}\right)^{i-a} K_{a,i,t,k} * ck_{a,i,t,k}^{1-\frac{1}{\gamma}}, \tag{4.3}$$

where $P_{a,i,t}$ is the probability that an adult agent who is age a at time t will survive to age i, $c(a,i,t,k)$ is the age-i consumption of an agent in skill class k who is age a at time t, $l(a,i,t,k)$ is the age-i leisure of an agent in skill class k who is age a at time t, $K_{a,i,t,k}$ is the number of children of an agent age a at time t in skill class k when the agent is age i, and $c_K(a,i,t,k)$ is consumption per-child at time t of an agent age a in skill class k when the agent is age i.

The parameters $\delta, \rho, \varepsilon$ and γ denote the rate of time preference, the intratemporal elasticity of substitution between consumption and leisure, the leisure preference parameter, and the intertemporal elasticity of substitution between consumption and leisure, respectively.

The probability of an agent age a at time t surviving to age i is

$$P_{a,i,t} = \prod_{z=a}^{i} [1 - d_{a,z,t}], \tag{4.4}$$

where $d_{a,z,t}$ is the agent's probability of dying at age z conditional on surviving to that age.

The assets $\mathrm{A}_{a,t,k}$ of a skill-k agent who is age a at time t evolve according to

$$\mathrm{A}_{a+1,t+1,k} = \big[\mathrm{A}_{a,t,k} + I_{a,t,k}\big](R_{t+1}) + w_{a,t,k}\big[h_{a,t} - \ell_{a,t,k}\big] - T_{a,t,k} - C_{a,t,k}, \tag{4.5}$$

where r_t is the pre-tax return on investment, $C_{a,t,k}$ corresponds to the aggregate consumption i.e. $c_{a,t,k} + K_{a,t,k} * ck_{a,t,k}$; $I_{a,t,k}$ are inheritances received in year t, $h_{a,t,k}$ is the endowment of time, $T_{a,t,k}$ is net taxes (taxes paid net of pension, disability, and other transfer payments received). $T_{a,t,k}$ includes all taxes, including taxes on asset income, taxes on labor income, and consumption taxes.

Labor income of an agent in year i is the product of her labor supply and wage. The latter is the product of the skill-specific wage rate $w_{k,i}$ in year i and age- and year-specific productivity per time-unit $E(a,i)$.

Net taxes, $T_{l,t,k}$, include consumption, capital income, and progressive income taxes as well as social security contributions. It is net of pension and disability benefits received in the form of transfer payments. Given the assumed ceiling on payroll tax contributions, payroll tax rates, both average and marginal, differ across agents. Each agent's pension benefits depend on their pre-retirement earnings history. In contrast disability benefits are provided on a per capita basis. Finally, households receive a transfer financed by corporate taxes. These rebates reconcile the observed high marginal corporate tax rates with low revenues.

To calculate $I_{a,t,k}$, we sum together all bequests within a skill class and distribute them by age. While there are no true family units in the model, this is meant to mimic younger individuals leaving bequests to their spouses or friends. Private assets of all agents who died are aggregated and then distributed according to an endogenous age-dependent distribution scheme $\Gamma_{l,t}$ to all agents aged between 23 and 67. These bounds are the maximum age of death minus the minimum age of fertility, and the minimum age of death minus the maximum age of fertility. To be precise, the inheritance of agents age l in year t is given by:

$$I_{l,t,k} = \Gamma_{l,t} \frac{\bar{A}_{t,k}}{N_{l,t,k}} \qquad \text{where} \quad \sum_{l=23}^{67} \Gamma_{l,t} = 1. \tag{4.6}$$

The denominator $N_{l,t,k}$ counts the number of agents alive at the end of period t. The numerator in this ratio measures the aggregate assets of skill-class k agents who die in year t. A share $\Gamma_{l,t}$ of these bequests is dedicated to inheritants aged l of the same skill class. This share is split equally among all agents of the same age and skill group. $\Gamma_{l,t}$ is the distribution of the ages of children of individuals dying in that year.

As in (Altig et al., 2001) and (Kotlikoff et al., 2007), we model technical progress as permitting successive generations to use time more effectively. We implement this assumption by letting the time endowment of successive generations in each region grow at the common rate λ. The time endowment of an agent age a at time t is denoted by $h_{a,t}$:

$$h_{a,t} = (1 + \lambda) * h_{a,t-1}. \tag{4.7}$$

This treatment of technical change ensures eventual convergence of the economy to a long-run balanced growth path. Other formulations of technical change, such as making it labor-augmenting, preclude a steady state given the model's preferences. This would prevent us from using our iterative method for determining the model's equilibrium transition path.[34]

Given interest rates r_t and wages $w_{k,t}$, agents maximize utility (4.1) subject to the intertemporal budget constraint (4.5) and the constraint that leisure in each period does not exceed their time endowment (i.e. $\ell_{l,t,k} \leq h_{l,t}$). They do this by choosing their leisure and consumption demands, i.e., $\ell_{l,t,k}, c_{a,t,k}$, and $ck_{a,t,k}$ where $ck_{a,t,k}$ is the consumption of the children of relevant parents.

Given individual consumption and leisure, agents' asset levels are derived from (4.5). Aggregate values of assets, private consumption goods, and labor supply obey:

$$A_{t+1} = \sum_{k=1}^{2} \sum_{a=21}^{90} \underbrace{\mathrm{a}(a+1, t+1, k) N_{a,t,k}}_{\bar{A}(a+1,t+1,k)}, \tag{4.8}$$

$$C_t = \sum_{k=1}^{2} \sum_{a=21}^{90} \left[c_{a,t,k} + KID_{a,t,k} * ck_{a,t,k}\right] N_{a,t,k}, \tag{4.9}$$

$$L_{k,t} = \sum_{a=21}^{90} E(a,t) \left[h_{a,t} - \ell_{a,t,k}\right] N_{a,t,k}. \tag{4.10}$$

Since households die at the beginning of each period, we aggregate across all agents alive at the end of the prior period to compute $\bar{A}(a+1, t+1, k)$, which is used in the calculation of bequests (see (4.6)). Total assets of agents alive at the end of period $t+1$ can be written as

$$\mathcal{A}_{t+1} = \sum_{k=1}^{2} \sum_{a=21}^{90} \mathrm{a}(a, t+1, k) N(a, t+1, k), \tag{4.11}$$

which includes the assets of immigrants in period $t+1$.

4.3.3 The Production Sector

Each region's GDP equals the sum of an energy-endowment flow X_t and aggregate non-energy output Y_t:

$$GDP_t = Y_t + X_t. \tag{4.12}$$

Why include energy? Most macroeconomic do not explicitly model fossil fuel production. For our purposes, it is important for its role as a major public and private asset, especially in Russia. We model the endowment of energy in each country as generating an annual flow of the model's single consumption and investment good. The flow is net of extraction costs. The size of the endowment is based on the actual distribution of fossil fuel profits, as discussed in the calibration section. All regions exhaust their energy resources at the same time.

The model specifies the size of the global energy flow, how it is distributed across regions, and the share of each region's flow owned by the government. The government's share of its region's flow of energy rents is treated as a receipt. The flow of energy in each country is constant throughout time to the point of exhaustion. Since the global economy grows, GDP originating in the fossil-fuel sector declines each year through 2083 (when exhaustion occurs) as a share of world GDP.

Energy flow not owned by the government is a private asset in our model. The model's total private assets are the sum of government bonds, capital, and privately owned energy flows. Individuals may hold negative assets on which they pay the domestic interest rate, so there is also a fourth asset (private debt), but this is in zero net supply. Arbitrage and perfect foresight ensures that all assets earn the same return and that agents are indifferent with respect to the composition of their their portfolio.

Non-energy output is produced via a Cobb-Douglas technology that uses capital

K_t and two types of labor $L_{k,t}$, i.e.:

$$Y_t = \phi K(t)^{\alpha} L(1,t)^{\beta_l} L(2,t)^{\beta_h}, \tag{4.13}$$

where α is the share of capital income in production, β_l is the share of low-skilled labor input, β_h is the share of high-skilled labor input, and $\alpha + \beta_l + \beta_h = 1$. The parameter ϕ is the total factor productivity.

Firms maximize profits π_t,

$$\pi_t = Y_t - \sum_{k=1}^{2} w_{k,t} * L_{k,t} - (r_t + \delta_k)K_t - T_t^k, \tag{4.14}$$

where $w_{1,t}$ is the wage of low-skilled workers, $w_{2,t}$ is the wage of high-skilled workers, and r_t is capital's rental rate.

Profit maximization requires

$$w_{1,t} = \beta_l \phi K_t^{\alpha} L_{1,t}^{\beta_l - 1} L_{2,t}^{\beta_h}, \tag{4.15}$$

$$w_{2,t} = \beta_2 \phi K_t^{\alpha} L_{1,t}^{\beta_l} L_{2,t}^{\beta_h - 1}, and \tag{4.16}$$

$$r_t = (1 - \tau_t^k) \left(\alpha \phi K_t^{\alpha - 1} L_{1,t}^{\beta_l} L_{2,t}^{\beta_h} - \delta_K \right). \tag{4.17}$$

4.3.4 The Government Sector

Each region's government pays for general expenditures via new borrowing, ΔB_t, energy-sector revenue X_t^g, and taxes collected from households and firms. General expenditures consist of purchases of goods and services C_t^g, payment for pension, health care, and disability benefits that are not covered via payroll taxes, and interest on existing debt:

$$\Delta B_t + X_t^g + \sum_{k=1}^{2} \sum_{a=21}^{90} T_{a,t,k} N_{a,t,k} + T_t^k = C_t^g + \varrho S B_t + r_t B_t, \tag{4.18}$$

where ϱ denotes the share of these transfer payments financed by general revenues.

Revenues

To generate realistic marginal and average corporate tax rates, we assume that households receive a rebate of a fraction of their gross corporate tax revenues, T_t^k, via a lump-sum transfer, $T_{a,t,k}$. The progressivity of income taxation follows (Auerbach and Kotlikoff, 1987) where average income tax rates rise with the income-tax base.

Corporate taxes T_t^k equal the corporate tax rate τ_t^k times output net of labor costs and depreciation.

$$T_t^k = \tau_t^k[Y_t - \sum_{k=1}^{2} w_{k,t}L_{k,t} - \delta_K K_t] \tag{4.19}$$

Individuals are also taxed on their labor income. Let PY_t reference the aggregate payroll-tax base. This tax base differs from total labor earnings due to the ceiling on taxable wages. This ceiling is fixed at 290, 200, 155, 300, and 300 percent of average income in the U.S., Europe, Japan plus Korea, China, and India, respectively. Japan+'s ceiling is set at Japan's 2012 level (OECD, 2013). For Russia, there is no ceiling. Table 4.1 shows median income and the taxable earnings using these assumptions.

Table 4.1: Household Income and Taxable Ceiling*

Country	Household Median Income (US$)	Ceiling on Taxable Wages (%)	Maximum Taxable Earnings (US$)
USA	43,585.0	290	126,396.5
EU	28,544.5	200	57,089.0
Japan+	37,341.5	155	57,879.3
China	7,870.0	300	23,610.0
India	3,600.0	300	10,800.0
Russia	11,724.0	–	–

* International Labour Organization (ILO) statistics

The sum of the average employer plus employee payroll tax rates $\hat{\tau}_t^p$ for the pension and disability transfer programs are based on each region's transfer-program-specific $(1-\varrho)$ budget (SB_t):

$$\hat{\tau}_t^p PY_t = (1-\varrho)SB_t. \tag{4.20}$$

Due to contribution ceilings, statutory payroll-tax rates can differ from the average payroll tax rate. Above the contribution ceiling, marginal social security contributions are zero and average social security contributions fall with the agent's income. To accommodate this non-convexity in the budget constraint, we assume that the highest earnings class in each region with a payroll tax ceiling (i.e., all regions except Russia) pays payroll taxes up to the relevant ceiling, but faces no payroll taxation at the margin.

Expenditures

General government expenditures, C_t^g, consist of government purchases of goods and services, including educational expenditures and health outlays. General government purchases (e.g. on military spending) are fixed as a share of non-energy sector output.Age-specific per capita purchases (i.e. on health, education) grow at the rate of non-energy sector output growth. Consequently, aggregate expenditures adjust with changes in the size and age structure of the population.

Age-specific health outlays grow with Y_t. However, in the U.S., Europe, Japan+, and Russia, we assume an additional growth rate of 1.0 percent per year between 2013 and 2035.[35] In China and India, age-specific health care outlays per capita are assumed to grow at a faster pace: For the first 35 years after the 2013 transition there is an additional annual growth rate of four percent. All government health benefits are treated as government consumption, whereas disability benefits are treated as fungible transfers to households.

During the transition, the governments in the U.S., Europe, Japan+, Russia, and India maintain their initial debt-to-GDP ratios. By assuming a fixed debt-to-GDP ratio, we take as given that countries will always be committed to keep their fiscal balances under control. We also keep the ratio of income-tax to consumption-tax revenue fixed each year and balance the government's annual budget (4.18) by adjusting the intercept in our linear equation determining the average income-tax rate as well as the consumption-tax rate.

As for pension benefits, consider an agent who retires in year i at the exogenously set retirement age $\bar{a}_i$. Her pension benefit $Pen_{a,t,k}$ in year $t \geq i$ when she is age $a \geq \bar{a}_i$ is assumed to linearly depend on her average earnings during her working life $\bar{W}_{i,k}$. Thus,

$$Pen_{a,t,k} = \nu_1 \times \bar{W}_{i,k}. \tag{4.21}$$

4.3.5 Solution algorithm

Baseline (Non-Autarky) Transition

Given initial conditions for individual asset holdings, our initial guesses of tax rates/tax function parameters as well as of the time paths of region-specific capital stocks, wage rates, and marginal products of capital, we calculate the world interest rate in all periods using the first-order condition determining U.S. demand for capital. We then use this new path for the interest rate to update the capital stocks in all regions except the U.S. Using the world distribution of capital in every period, we solve for household consumption, savings, and labor supply decisions.

Aggregating individual labor supplies in each year provides new time paths of aggregate region-specific labor supplies. Next we aggregate agent-specific assets at each date to determine a time-path of aggregate world-wide asset holdings. Given capital demand in Europe, Japan+, Russia, China, and India, we can calculate the new capital stock in the U.S. as the difference between world-wide asset holdings and capital demand in the remaining regions. The new values for the aggregate supplies of capital in the U.S. and labor in each region/year are then weighted with the initial guesses of these variables to form new guesses of their time paths.

The next step in our algorithm is to calculate new wage rates and use the annual revenues and Social Security benefit payments implied by the household decisions to update annual tax rates/tax parameters. We also update corporate tax transfers to households. The algorithm iterates until the region-specific time paths of capital stocks and labor supplies converge to a fixed point. Markets (i.e. supply and demand for goods) are then confirmed to clear to many degrees of precision. We give our economy 300 years to reach a balanced growth path. This is ample time, as our model reaches a steady state to many decimal places decades earlier.

Post-Sanction Transition

The model simulates maximally severe multilateral sanctions imposed on Russia, harsh enough to induce a state of autarky. In year 2012, trade is possible. In 2013, simulated sanctions enter into effect. When trade is denied, Russia can respond in three ways: a) allow for foreign capital flight; b) seize foreign assets and/or c) default on debt owned by foreign investors. These scenarios are not unrealistic. For instance, Russia drafted a bill that would allow the government to seize foreign assets in the country in response to Western economic sanctions. The so called "Rotenberg Bill" was passed after the Russian businessman Arkady Rotenberg had 30 million Euro of assets seized by the Italian government.

An autarky shock is simulated in the model by the following procedure. First, state parameters in 2013 are taken as exogenous from the initial run. Then, these state parameters, as well as all parameters governing fiscal policy or demographics, are copied onto all other nations. Because all six nations in the model are now identical, no meaningful trade can occur, placing each copy of Russia into effective autarky.

In the constant assets scenario, the personal assets held by Russians in 2013 are held fixed. In the government seizure scenario, the Russian government gains additional assets such that the Russian stock of capital in 2013 is equal to its non-autarkic level. Russian private assets remain fixed. In the productivity shock scenario, Russia's productivity convergence with the US is reduced by 25% immediately, and then converges linearly to the US rate over the century. In all scenarios, Russia's energy flows are reduced by 75%.

4.4 Calibration

This section first presents our demographic calibration. Next, we explain the calibration of the model's productive technologies and preferences. Finally, we discuss our fiscal calibration.[36]

Population Projections Through 2050

Our model generates demographic projections based on the population by age at the beginning of 2008 for each country. The model's age-, year-, and country-specific fertility, mortality, and immigration rates are calibrated to match official projections through 2058. After 2058, fertility rates are endogenously set each year to stabilize total births. This entails gradual changes in fertility rates that lead, over time, in conjunction with our assumed stable net immigration rates, to a stable population and age structure in each region.[37]

Each country's workforce consists of high- and low-skilled workers. We assume that 30 percent of the U.S., European, Japanese+ and Russian work forces are high-skilled. This is in line with figures on educational attainment from (Barro and Lee, 2001). For China and India, we assume that 25 percent of the workforce is high-skilled.

Table 4.2 compares official and simulated projections of total population, fertility rates, and age structures between 2013 and 2050. Since the model features self-fertilizing agents, long-run zero population growth entails a fertility rate of 1, not 2, ignoring net migration and infant mortality (i.e., each agent needs to reproduce herself, not herself and a sexual partner, to stabilize the population). In reporting the model's region- and year-specific fertility rates, we double the model's rates for comparability with real-world projected rates.

Table 4.2: Comparing Actual and Simulated Population Projections

Country	U.S.		EU		Japan+		China		India		Russia	
Year	2013	2050	2013	2050	2013	2050	2013	2050	2013	2050	2013	2050
Total Population (in millions)												
Model	319.4	402.6	510.4	500.2	176.8	154.4	1364.5	1401.5	1256.0	1623.9	141.9	134.1
Official	319.9	400.9	509.2	511.6	176.3	159.4	1384.9	1385.0	1251.7	1620.1	142.7	131.1
Fertility Rate												
Model	2.04	1.85	1.55	1.82	1.42	1.49	1.68	1.85	2.56	1.85	1.48	1.53
Official	1.97	1.99	1.58	1.83	1.41	1.73	1.66	1.81	2.50	1.92	1.53	1.69
Age Structure (percent of total population)												
0-9												
Model	13.61	11.76	9.89	10.03	9.42	7.34	12.50	10.76	20.43	12.06	11.99	9.28
Official	12.99	12.10	10.45	10.01	8.78	8.17	12.38	9.74	19.40	12.86	11.10	11.31
10-19												
Model	12.91	12.17	10.58	10.00	9.67	8.22	13.43	10.82	18.34	12.36	9.61	9.90
Official	13.39	12.19	10.50	9.94	10.09	8.52	12.49	10.00	19.10	13.52	9.99	11.34
20-29												
Model	13.80	12.33	12.13	10.84	11.43	8.83	15.60	10.84	16.51	12.74	14.11	9.76
Official	13.86	12.54	12.48	10.59	11.47	9.21	17.35	10.40	17.73	14.09	15.93	11.54
30-39												
Model	12.84	12.98	12.98	11.27	13.79	10.13	14.76	12.38	14.84	13.50	16.79	13.23
Official	13.07	12.42	13.79	11.43	13.83	9.87	14.73	12.46	14.86	14.31	15.44	13.65
40-49												
Model	12.98	12.51	15.28	11.58	14.68	11.28	17.27	11.66	11.86	14.15	13.86	12.68
Official	13.29	11.99	14.74	11.35	14.72	10.19	16.73	11.46	11.75	14.00	13.45	12.22
50-59												
Model	14.27	12.05	14.19	12.32	13.06	11.64	12.98	13.62	9.27	13.09	15.67	11.78
Official	13.62	11.76	13.67	11.55	13.09	11.86	12.40	13.13	8.79	12.91	15.07	11.47
60-69												
Model	11.05	11.90	12.25	13.04	12.73	13.93	9.41	14.92	6.19	12.45	12.37	18.49
Official	10.31	10.66	11.23	12.50	12.76	12.77	8.25	15.47	5.17	10.22	9.70	14.80
70-90												
Model	8.55	14.30	12.71	20.92	15.22	28.63	4.05	15.01	2.56	9.64	5.60	13.88
Official	9.47	16.34	13.13	22.64	15.26	29.41	5.68	17.34	3.20	8.09	9.33	13.68

The model reproduces official projections very closely. In Russia, for example, the model's 2013 population total differs from the official tally by only 0.5 percent. And the discrepancy in 2050 is only about 2 percent. Or consider the EU. In 2013 the model overstates the population count by less than 2 million people. In 2050, there is a larger discrepancy – an 11.4 million underestimate. But, again, this is only a 2 percent differential.

The model also does a remarkably good job tracking region-specific changes in population age distributions. The main exception here is with the elderly Russians. To keep easy track of bequests, our model requires that parents always predecease their children. As indicated, we set age 68 to be the earliest age at which one can die. At age 68, one's parents are definitely deceased since the youngest parent of a 68 year-old (who gave birth at age 23) would be age 91, and age 90 is the assumed maximum age of life. Ruling out death before age 68 makes replicating the Russian age distribution particularly difficult given the region's unusually high mortality rates in late middle age.

Official fertility rate projects are also closely approximated by our model. Take China for instance, which has official fertility rate estimates of 1.66 and 1.81 in 2013 and 2050, respectively. The corresponding model values are 1.68 and 1.85. Or compare Russia's projected increase in fertility rate from 1.53 in 2013 to 1.69 in 2050 with our model's 1.48 for 2013 and 1.53 value for 2050. Moreover, according to official projections, all six regions will age dramatically in coming decades. The model does a good overall job reproducing this process. For example, as shown in Table 4.2, the share of Russia's population over age 70 will be 13.7 percent in 2050 based on official forecasts and 13.9 according to our model.

4.4.1 Simulated Demographics, 2050 and 2100

Table 4.3 reports the model's population totals, fertility rates, and age structures for 2050 and 2100. All age-specific fertility rates after 2058 (the last year of our official fertility rate projections) are multiplied by a factor that leads each cohort to produce the same number of births at a given age as the cohort one year older produced at that age. The above, in addition to our assumption of constant age- and skill-specific immigration rates (after 2058), lead over time (after 90 years, to be precise), to a stable age distribution as well as population size in each region.

Note that projected population totals in 2100 can dramatically differ from those in 2058. Countries whose older single-age cohorts are larger in size than the number of newborns will experience population declines. The reason is simple. After 2058, all existing cohorts will gradually be replaced by new cohorts of equal size (ignoring any mortality after age 68) as the number of newborns in 2058.

Take Russia for example: Between 2050 and 2100, the population shrinks from 134.1 million to 102.1 million. This is true notwithstanding the gradual increase in Russia's fertility rate associated with our assumed post-1958 stabilization of the number of new births. Intuitively, below-replacement levels of fertility mean that there will be fewer child-bearing agents in the future than there are in the present. Thus the only way to obtain the same number of births, these smaller sized cohorts would need to have higher fertility rates when they reach their child-bearing ages.

Like Russia, the EU, Japan+, China, and India experience population declines between 2050 and 2100. The EU loses roughly 30 million people, Japan+ loses about 48.6 million, China experiences a reduction of almost a quarter of a million people, and India shrinks by almost 125 million. The U.S., in contrast, experiences a net increase of over 43 million over the second half of the century.

The last thing to highlight in the Table 4.3 is that fertility rates in China and

India end up above the model's 2.0 long-run population replacement-rate value. This reflects the assumption that these countries will experience net emigration – more people leaving then entering. In the other regions net immigration is positive meaning their ultimate fertility rates are below 2.0.

Each region reaches its long-run population distribution and level in 2148, 90 years after 2058, when total births by age are stabilized. Looking through the entire course of the century, the model predicts dramatic changes in absolute and relative population sizes. Japan's population shrinks by 40 percent, Russia's by 28 percent, the EU's by almost 8 percent, and China's by over 16 percent. In contrast, the U.S. population rises over the century by almost 39 percent. And India's population rises by almost 20 percent.

Table 4.3: Simulated Population Totals, Fertility Rates, and Age Structures, 2050 and 2100

Country	U.S.		EU		Japan+		China		India		Russia	
Year	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Total Population (in millions)												
	402.6	444.21	500.2	470.12	154.44	105.95	1401.5	1157.05	1623.9	1499.02	134.1	102.1
Fertility Rate												
	1.85	1.77	1.82	1.79	1.49	1.92	1.85	2.04	1.85	2.15	1.53	1.79
Age Structure (percent of total population)												
0-9	11.76	10.55	10.03	10.83	7.34	10.12	10.76	12.34	12.06	12.80	9.28	10.45
10-19	12.17	10.94	10.00	11.01	8.22	10.18	10.82	12.30	12.36	12.40	9.90	10.65
20-29	12.33	11.58	10.84	11.82	8.83	10.44	10.84	12.13	12.74	12.10	9.76	11.24
30-39	12.98	12.12	11.27	12.17	10.13	10.55	12.38	12.06	13.50	12.06	13.23	12.04
40-49	12.51	12.41	11.58	12.27	11.28	10.58	11.66	12.03	14.15	12.05	13.68	12.66
50-59	12.05	12.67	12.32	12.19	11.64	11.18	13.62	12.71	13.09	12.30	11.78	14.66
60-69	11.90	12.73	13.04	11.99	13.93	12.42	14.92	12.81	12.45	13.01	18.49	15.32
70-90	14.30	16.99	20.92	17.73	28.63	24.52	15.01	13.62	9.64	13.28	13.88	12.98

4.4.2 Production, Preference and Policy Parameters

Table 4.4 shows the parameters of our production technology. Table 4.5 reports values of preference and policy parameters. Capital's share of production is set according to Institut der Deutschen Wirtschaft (2009). The output shares of the low- and high-skill groups were set to generate a roughly 50 percent wage differential between the two groups. The depreciation rate is set at 7.5 percent.

Table 4.4: Production Parameters

	Symbol	Value
Capital share in production	α	0.35
Low-skilled labor share ($k = 1$)	β_l	0.40
High-skilled labor share ($k = 2$)	β_h	0.25
Technology coefficient	ϕ	1.00
Depreciation rate	δ_K	0.075

Table 4.5: Preference, Productivity and Policy Parameters in 2013

	Symbol	U.S.	EU	Japan+	China	India	Russia
Time preference rate (approximate)	δ	-0.0146	-0.0510	-0.0220	-0.0560	-0.0030	-0.0091
Intertemporal elasticity of substitution	γ	0.25	0.25	0.25	0.25	0.25	0.25
Intratemporal elasticity of substitution	ρ	0.4	0.4	0.4	0.4	0.4	0.4
Leisure preference parameter	ε	1.5	1.5	1.5	1.5	1.5	1.5
Shift parameter for productivity	ξ	1.00	0.420	0.530	0.095	0.051	0.212
Technical progress	λ	0.01	0.01	0.01	0.01	0.01	0.01
Wage tax progressivity (in %)	φ	0.3	0.3	0.3	0	0	0
Age of retirement	$\bar{a}$	63	65	60	60	60	58
Corporate Tax Rate Rebate (in %)	τ^c	49.0	8.0	0.0	0.0	20.0	10.0
Corporate Tax Rate (in %)	τ^c	40.0	22.8	35.2	25.0	34.0	20.0

Time-preference rates in the six regions were calibrated to match the model's 2013 region-specific ratios of private consumption to GDP. The intertemporal elasticity of substitution, the elasticity of substitution between consumption and leisure, and the leisure preference parameters are taken from (Kotlikoff et al., 2007).

The age- and year-specific productivity profile of a low- or high-skilled worker age a in period t is given by:

$$E_{a,t} = \xi_t e^{4.47+0.033(a-20)-0.00067(a-20)^2}(1+\lambda)^{a-21}, \tag{4.22}$$

The above profile is that used by Auerbach and Kotlikoff (1987). Note that the higher the rate of technological change, λ, the steeper the age-ability profile. This captures the role of technical progress in influencing not just the level, but also the shape of longitudinal age-earnings profiles. The labor productivity parameter ξ is country specific. It determines the productivity in a given country of time-t cohort entering the labor market. The U.S. value of ξ variable is time invariant and normalized at 1. The calibration of this parameter for other regions is described in the following subsection.

Retirement ages – the ages at which agents stop working and also start collecting their state pensions – are taken from the OECD (2014) for the U.S. and Europe, from World Bank [38] for Japan+, China, and India, and from the Russian Ministry of Finance.

4.4.3 Calibrating Government and National Accounts

We chose region-specific values for the following parameters to match official government and national account data in 2013 as closely as possible: the initial productivity parameter, ξ, the time preference rate, δ, income and corporate tax rates, the mix of income versus consumption taxes (that we use to stabilize debt-to-GDP ratios), the percentage in each region of corporate taxes that is rebated, the pension-income replacement rate, the share of fossil-fuel endowment flow contributing to the GDP of each country, the share of energy revenues collected by each government, the overall contribution of fossil fuels to GDP, and the initial levels of disability, health, education, and other government expenditures.

National Accounts

GDP (PPP) is taken from IMF (2014). Government revenue and expenditure data as well as other national account data for Europe, Japan+, and the U.S. are taken from IMF (2014) and the World Bank's World Development Indicators (WDI, 2015). For some regions the reported data reflects our best judgment on how to classify expenditures by functions. For China, India, and Russia, these figures are calculated using publicly available data from their respective ministries of finance following the GFS manual. Energy-sector rents are the sum of World Bank oil, gas and coal resource rents, defined as the difference between revenues and extraction costs for the year 2012 (World Bank, 2015).

Table 4.6 compares the model's 2013 values of GDP and other variables with actual values. Each country's GDP, including GDP from its energy sector, is presented as a share of U.S.'s 2013 GDP. As clearly stated in the table, the model generally does a very good job matching actual 2013 relative GDPs and ratios of private and government consumption to GDP. And it does a reasonable job matching actual aggregate- and category-specific expenditure ratios to GDP. For non-U.S. regions, the initial values of ξ parameter are set to help reproduce the 2013 relative values of GDP and are gradually raised to 1 (i.e., to parity with the U.S.) for each successive cohort of new workers. For Europe, Japan+, China, India, and Russia we assume this adjustment occurs over 25, 25, 40, 95, and 40 years, respectively. We have no solid basis for these choices other than the production of plausible relative GDP ratios in 2050. Our assumption of such a slow catch up for India was influenced by the findings of (Bosworth and Collins, 2008), which show very little improvement in elementary education attainment in that country over the past four decades. Finally, the model's 2013 ratio of household consumption to GDP is calibrated by adjusting the time preference rate of different regions.

In addition to these parameter values, our model requires an initial distribution of assets by age and income class for each region. We generate the country-age-income class asset distribution by calculating the steady state of the model using

2008 demographics and parameters. The level of each region's asset profile is then adjusted to generate plausible interest rates and ratios of assets between regions.

Fiscal Accounts

Since revenue must adjust to expenditures or vice versa, one can't separately calibrate on both revenues and expenditures. We chose to calibrate on expenditures, which is why they match up to actual data far more closely than the model's endogenously determined revenue amounts.

Each region is assumed to adjust income and consumption taxes to maintain its 2013 debt-to-GDP ratio through time. In 2013, debt-to-GDP ratios are calibrated to match 2013 government net-interest payments. We exogenously set the corporate tax rate to match the official nominal rate (see Table 4.5). To match actual corporate tax revenues relative to GDP, we assume each nation rebates a percentage of corporate tax revenues as a lump-sum transfer (see Table 4.5).

The remaining revenue collected in 2013 comes from consumption and income taxes. The consumption-tax shares of these remaining revenues are 53, 58, 48, 93, 85, and 75 percent for the U.S., EU, Japan+, China, India, and Russia, respectively. In each year of the model's transition, we multiply the 2013 region-specific consumption- and income-tax shares by the amount of revenues needed to keep debt fixed as a share of GDP in that year. This determines each year's total consumption- and income-tax revenues. The model's annual consumption and income tax rates are then set to generate these revenue amounts.

Our income tax systems are assumed to be progressive with the parameters of each region's income-tax functions set to generate what appears to be realistic average and marginal tax rates. Revenues raised from the income tax satisfy

$$R_t = \tau_t I_t + \frac{\varphi_t I_t^2}{2}, \tag{4.23}$$

where R_t is total revenues from the income tax, τ_t is the endogenously calculated average income tax rate, I_t is total labor income, and φ_t an exogenously set progressivity term. For the U.S., the EU, and Japan this takes the value of 0.3. For the other three regions it is 0.

Under this calibration, the 2013 average U.S. income tax rate is 13.1 percent and the average marginal income tax rates on unskilled and skilled workers are 24.5 and 34.1 percent, respectively.

Outlays of social security systems were calibrated to yield official values from the IMF (2014) and WDI (2015). The level of benefits is calibrated by setting the pension replacement rate. The replacement rates for the U.S., EU, Japan+, China, India, and Russia are set at 71.7, 81.5, 24, 27, 60, and 63 percent respectively. The percentage of pensions paid via a dedicated payroll tax is constant and calibrated based on the 2013 ratio of payroll tax revenues to benefits. For the U.S., 35 percent of pension benefits are paid via general government revenues. For the EU, Japan+, China, India, and Russia the percentages are 6.4, 5, 40, 55, and 21, respectively.

Due to data limitations we use the German age-specific education profile for all regions in the model and re-scale the profile on a country-specific basis to get realistic education outlays in year 2013 in each region. Education expenditures and 'other expenditures', which include military spending and other government services, are calibrated in the same way. We assume that the level of disability transfers grows with the rate of technological growth, that health expenditures grow as described above, and that education and other expenditures remain constant as a share of non-fossil fuel output (GDP less energy sector rents).

When calibrating health expenditures, we apply the Japanese age-specific government health care expenditure profile for Japan+ as well as for China and India. In the case of Europe, we use the German profile. For the U.S., our profile comes from (Hagist et al., 2009). The Swedish profile from that study is used for Russia. These profiles are then multiplied by a country-specific factor to reproduce the 2013 ratio of health expenditures to GDP.

We assume, for all countries, that disability benefits paid per agent are the same regardless of age. The level of disability benefits in each region is calibrated to match the 'other transfers' share of national public expenditures.

4.5 Results

In this section, we present the results of the model. The chapter begins by presenting the baseline simulation. The baseline scenario begins in 2013. It assumes that there will be no restrictions on trade.

The chapter then considers the impact of multilateral sanctions imposed on Russia. We consider three scenarios, and variations on them. The first, capital flight, assumes that any Russian capital abroad is swapped for foreign owned Russian capital and vice-versa. Russia has a net-negative investment position, so this leads to a reduction in Russian domestic capital as excess foreign assets are repatriated. The second, capital seizure, assumes that all Russian assets abroad are immediately repatriated, and that any foreign owned capital in Russia is confiscated by the government. The third scenario adds a productivity shock.

GDP in the Baseline Transition

As in reality, in the baseline simulations 2013 'global' GDP [39] is about four times that of the U.S. The model projects that the global economy through 2100 will experience tremendous economic growth. This is shown in Table 4.7. The table indicates the evolution of GDP, the capital stock, labor supply, and tax rates along the baseline path. GDP, capital stocks, and labor supplies are written as ratios of their 2013 U.S. counterparts. [40] In 2100 global GDP is projected to be about 25 times larger than the 2013 U.S. GDP. Total output rises by a factor of 6.

Over this period, countries' shares of world GDP change dramatically (see Figure 4·2). Thanks to China's fast productivity catch up and India's massive population growth, the emerging East surpasses all other countries by mid-century. Together, China and India account for 34.5 percent of the 2013 global output. In 2100, the two countries account for 68.4 percent of global output. The E.U. faces a decline in its share of global GDP, as do Japan+ and Russia. However, Russia's economy surpasses Japan+'s by 2060. In 2100 Russia accounts for 3.2 % of world's GDP while Japan only accounts for 2.3%.

The primary driver of these results lies in differential population growth.[41] Other important factors are the productivity catch up and capital accumulation.[42]

Even in the year 2100 India is less productive than the U.S. This is due to the form of our assumption on labor-productivity catch-up. As the catch-up occurs for new cohorts, it takes roughly four decades for all workers in caught-up regions to have the same productivity as their same age peers in the U.S. In other words, cohorts of workers in each country enter with increasing productivities, but do not see catchup growth after they enter the workforce. In 2100 Chinese workers are fully caught up. However India, despite having fully productive new cohorts, still has older cohorts of less productive workers.

Population and labor productivity growth are the primary determinants of total effective labor supply, as labor supply within a country is not particularly elastic to the wage. Figures 4·4 and 4·5 show the effective labor supplies of low and high-skilled workers relative to their 2013 values. China and India again show the largest increases. Countries like China and Russia see their populations shrink relative to the U.S. (as is shown in Table 4.3). However, because their productivity catch ups with the U.S., their effective work forces grow by factors of roughly 8 and 5, respectively.[43] This explains evolution of their labor supply in Figures 4·4 and 4·5. India, in contrast, has a population increase that surpasses all other regions. Thus, despite not having fully caught up with the U.S. in terms of productivity, they have a dramatic increase in their effective work force. All other countries also experience catch-up growth. For Japan and the E.U., the catch up is smaller, because their productivities are closer to the US's in 2013. For both of these countries, the effective work force shrinks through time due to a declining population. Consequently, Japan's effective labor force grows at a slower rate than that of the U.S., which experiences rapid labor force growth, despite lacking productivity catch-up growth.

Changes through time in the model's country-specific capital stocks generally align with changes in each country's effective labor supply. Table 4.8, which shows relatively stable pre-tax marginal products of capital and labor, confirms this point (as the production function is homogeneous of degree one). Consider, for example, the gross marginal product of capital in the U.S., which depends on the capital-labor ratio. It is 14.4 percent in 2013 and approximately 17.0 percent after 2060.

Differences across the countries in gross marginal products reflect differences in their marginal (before rebate) corporate income tax rates. Since capital's completely unhindered mobility in the baseline simulation leads to equalization across regions in the post corporate-tax return to capital (as confirmed in Table 4.8), any regional differences in pre-tax returns (the marginal products of capital) arise due to differences across regions in rates of corporate income taxation.

Capital stock dynamics impact the wage rates in the six regions. Table 4.8

shows wage rates across the six regions. The marginal products of labor tell us the additional output that a 30-year-old of a particular skill type (who is endowed with the productive capacity of an equally skilled 30-year-old U.S. worker) would produce in the specified country in the year under consideration. There are interesting and easily explained regional differences here. For example, the U.S., due to its relatively high corporate income tax rate, has less capital per worker and, therefore, somewhat lower marginal products of low-skilled labor compared with E.U. or Russia. Another interesting feature is the relatively high marginal products of skilled workers in China and India. This reflects the initial and assumed ongoing scarcity of skilled relative to unskilled workers in these regions.

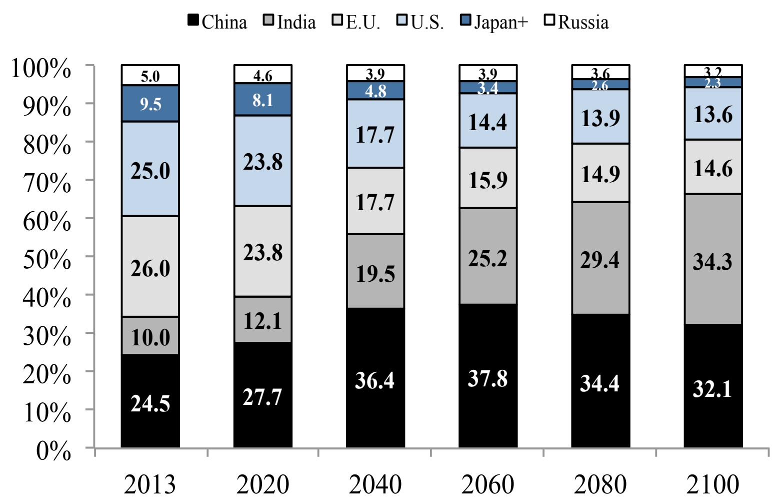
A workers in a given country in year t will not be as productive as her counterpart in the U.S. until the productivity catch up is complete. Consequently, the wage rates in the non-U.S. countries are considerably lower than in the U.S. in 2013 and for many years thereafter. In Russia in 2020, for example, a thirty year-old low-skilled worker earns only 44 percent of her U.S. counterpart's wage. However, by 2080, the gap is closed. Russian wages are higher due to a larger ratio of capital to labor in the country, which, in turn, is due to Russia's relatively low corporate tax.

Fiscal Policy in the Baseline Transition

The baseline scenario is optimistic for output, yet less rosy about government finances. Table 7 displays income, pension, and consumption tax rates across regions and time. In every country tax rates increase.

The model assumes that authorities are committed to a fixed debt-to-GDP ratio. Since we are interested on studying how fiscal burdens impact the different agents of the economy, we calibrated the model on the interest payments in 2013. There is only one interest rate in the model, so we represent agents which are able to borrow

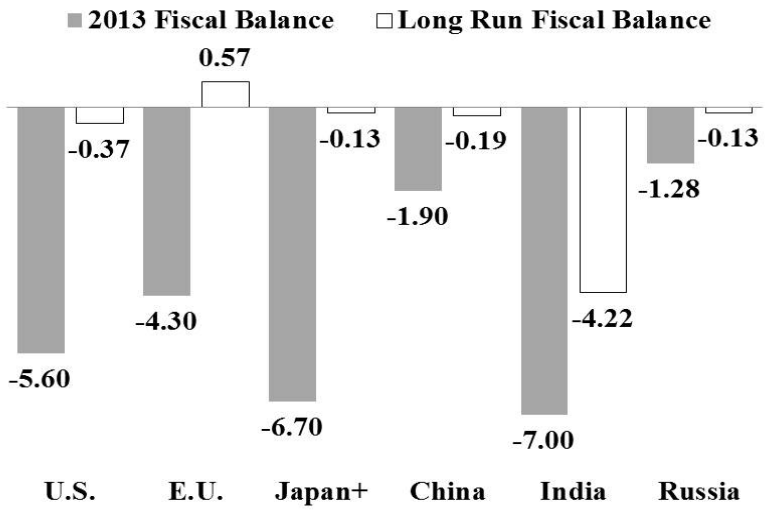
Figure 4·2: Country's Share of Global GDP



at reduced rates in the real world as having lower debt-to-GDP ratios. In 2013 the U.S. debt ratio was about 80 percent of GDP. However, because the U.S. pays such low interest rates, we represent this in the model as an effective debt-to-GDP ratio of .17. Russia, which pays higher interest rates in reality, has an effective debt-to-GDP ratio of .13 (compared to .10 in 2013 in reality). Keeping a fixed debt-to-GDP ratio comes at a cost. Over time public spending expands, forcing the government to raise income and consumption taxes to keep the deficit under control. Figure 4·3 attests to this.

In the U.S. case, the sum of the income, pension, and consumption tax rates is 43 percent in 2013 (where the consumption tax is measured as an equivalent tax on wages[44]). Average marginal tax rates are 47.6 and 48.8 percent respectively for unskilled and skilled U.S. workers in 2013. By 2100, these tax rates are 75.3 and 70.8 percent, respectively. Russia follows a similar pattern, with the average rate increasing from 39.6 to 74.6 percent over the century. Additionally, marginal tax rates in 2013 are 35.7 and 22.1 percent for unskilled and skilled workers respectively. In 2100 these increase to 65.7 and 44.4 percent. U.S. marginal tax rates on the higher

Figure 4·3: Fiscal Deficit as Share of GDP



paid skilled workers are therefore initially slightly higher and ultimately lower than those of the unskilled workers. This is because of the ceiling on taxable pension income that leaves high skilled workers paying no payroll tax at the margin.

The rise in the total effective wage tax rate is less pronounced in the E.U. The 2013 average is 57 percent, 1.5 times larger than the U.S. value. This narrows by 2100, when the E.U. total effective wage tax rate is 1.2 times that of the U.S. Thus the U.S. starts with a much lower total effective wage tax rate, but, at century's end, it closes the gap. Because the EU's productivity converges to that of the U.S. over the course of 25 years, in the year 2100 all E.U. workers have U.S. levels of productivity. However, pension benefits are calculated based on the lifetime wage of retirees and in 2100 reflect Europe's previously lower productivity.

Of the six regions, Russia faces the greatest challenges in financing government expenditures over the rest of this century. In 2013, its population age 60 and over accounted for less than 18 percent of the total. But by 2050, this age group represents over 34 percent of all Russians. Other things equal, this should necessitate a major increase in the tax needed to fund the Russian pension system. However, Russia's assumed catch-up somewhat makes up for this. In 2013, the average total wage tax equivalent tax rate in Russia is 35.7 percent. In 2060, it is not much higher -just 39.5 percent.

Russia's real fiscal crunch comes after 2083 with the global exhaustion of fossil fuel profits. In 2100 the average total effective wage tax rate is 65.7 percent. More than half of the increase in the Russian tax rate after 2060 reflects the loss of fossil fuel receipts. The rest reflects the projected continued aging of Russia after 2050 and resultant growth in pension and health care expenditure.

Russia, it should be noted, already has a very major problem with tax evasion. Its informal sector is very large, as reflected by the difference in its 22 percent statutory payroll tax rate and its 13.6 percent 2013 effective payroll tax rate. Hence, the prospect of a massive increase in tax rates toward the end of the century is particularly challenging for Russia.

Russia also experiences important changes in national saving. From a base of about 52 percent of GDP in 2013, private consumption increases to a peak of 74 percent of GDP in 2047. This increase is driven by the aging of the population. Subsequently, however, despite Russia's further aging, Russian private consumption drops steadily to 54.5 percent of GDP on the eve of fossil fuel exhaustion in 2083. This is due to Russians increasing their savings in anticipation of hard times.

In the model, income and substitution effects largely offset one another, i.e., the need to work due to the income loss from having to pay higher taxes balances the incentive to substitute leisure for consumption. Thanks to this, the model can converge regardless of high marginal tax rates. Although the model converges, in its current design, the model includes neither tax avoidance, tax evasion, or any political barriers to such high taxation. Were we to incorporate these two important factors in the model, financing projected future expenditure might be impossible.

4.5.1 Russia Under Autarky

A permanent disruption of trade leaves Russia in a particularly tenuous position. If Russia chooses not to make dramatic cuts to spending, then it will need to increase taxes, institute growth-enhancing reforms, or resort to other policies to mitigate the negative effects.

We consider two main autarky scenarios. In the first, Russia loses a large share of its domestic capital stock as foreigners repatriate their assets in Russia and vice versa. In the second scenario, Russia seizes foreign investors' assets located in Russia, keeping Russia's domestic capital stock constant.

We also consider variations on these scenarios. In one, Russian oil rents are assumed to decrease by 75 percent. In another, Russia experiences a productivity shock contemporaneous with being forced into autarky.

4.5.2 Capital Flight with Fossil Fuel Rent Reduction

In the first scenario, after sanctions are announced, but before they are implemented, all capital is repatriated by its owners. What does foreign capital flight imply for the country? A quick review of the facts can provide a hint. Historically, Russia has had a net positive international investment position (NIIP), which means that they are net lenders. The NIIP in 2015 was at about 23 percent GDP (up from 6 percent in 2013), with gross assets of 89 percent of GDP and liabilities of 66 percent of GDP. Moreover, from 2000 to 2013, the current account (CA) surplus fell from 18 to 2 percent of GDP, despite rising oil prices, as consumption increased rapidly. Thereafter, the post-2013 decline in oil prices has kept the CA below the 5 percent threshold. This behavior is reflected in the financial account which shows that, on average, Russians invest abroad more than what foreigners invest in Russia.

However, in the model, capital repatriation reduces the Russian capital stock by 77 percent. This is a dramatic loss of capital for the country that has a large immediate impact on output. In fact, in the initial year of the simulation, Russian GDP falls 43 percent below its baseline level. However, the Russian economy adapts over time. By 2100, Russia's GDP is only 1.4 percent below its baseline level. The capital is slowly replaced through savings. Labor supply also increases as Russians respond to a loss of income from much lower post tax wages. This is only slightly made up for by increased interest rates.

Why does our model imply that capital flight will lead to such a diminished stock of Russian capital? The answer is that foreigners tend to own particularly productive Russian assets, such as equities and real estate. In terms of the location of the investments, the NIIP compares the assets owned by Russians and held abroad against the assets owned by foreign citizens held in Russia. However, this comparison is not relevant in the model. When sanctions enter into effect, of the total amount of assets held in Russia, only those owned by foreign investors leave the country. However, the assets from Russian citizens held abroad stay put, leaving the country with only those domestically located. Thus in terms of the location of assets, Russia has a net borrower position. The amount of foreign assets held in Russia relative to local assets is substantially high. Therefore, when capital flight materializes and no further flows come into the country, total stocks fell in 77 percent. Is the 77 percent the relative foreign position? Yes, if Russia owned 100 percent of domestic oil and 100 percent of domestic bonds, then they only would be able to afford 23 percent of domestic capital.

The negative effects of a capital flight are further magnified by a decline of oil revenues. The assumed decline of the market value of fossil-fuel assets means that more of workers' savings are crowded into capital. While all Russians alive in 2013 are hurt by the decline in the fossil fuel price, elderly Russians are affected the most.

Cohorts entering retirement between 2008-2018 are severely affected by the sanctions. Generations born between 1970-1980 are worse off (at an average lifetime reduction in our utility measure of 20-30 percent), while future generations are impacted to a smaller extent. This is because they face lower wages and higher consumption taxes, which must be raised to make up for the shortfall. The young must pay higher taxes as well, but they have more time to adjust their labor supply and savings. Future generations are barely affected compared with the baseline, as fossil fuels exhaust in both scenarios.

The main mechanism for the immiseration of older Russian generations is an increase in consumption taxes. Household incomes decrease so tax rates must increase to make up for the lost fossil fuel revenue. Consumption taxes are about 4 times higher and income taxes are 1.3 percent larger than baseline in 2013 as a result of the changes. Tax rates remain around this level throughout most of the century.

Table 4.14 shows a comparison of our welfare measure for all scenarios. It helps to disentangle the effects of banning trade, capital repatriation, and the impact on oil prices. When contrasting autarky capital flight in presence and absence of an oil shock, it is clear that only about 10 percent of the observed loss in welfare is actually driven by capital flight. If Russia had not experienced the sharp fall of oil revenues, GDP would have declined about 30 percent (relative to the baseline) due to the fall of capital stocks. However, because oil revenues remain relatively higher, taxes do not increase as much. This reduces household consumption and welfare for all generations. The difference between experiencing capital flight with or without lower oil revenues reveals the Russia's medium-term policy challenges. When oil plays such a dominant role in the economy and oil price movements compound with the uncertain long-term impact of sanctions on saving-investment decisions, the normative external position may play against the country. The model predicts an important transition of the economy while resisting the stringent conditions. Along the transition path, Russia tightens its fiscal policy, thus rebuilding buffers and restoring capital stocks for future generations. Capital flight with an oil shock results in a tax burden about 4 times as severe as the scenario without the oil shock.

4.5.3 Capital Seizure with Fossil Fuel Rent Reduction

Suppose that instead of allowing capital repatriation, the Russian government seized domestic assets from foreign investors. This would prevent a massive withdrawal of capital, and give the government a large source of revenue moving forward. Realistic or not, there are certainly incentives for a government to investigate this policy, both as a way to stabilize the economy, and as a punishment to foreign sanctioners.

We consider the scenario in which after autarky is implemented, the capital stock is initially unchanged. Any capital that needs to be owned to reach this level is given to the government, leaving private Russian assets constant. Russia's debt-to-GDP ratio is kept constant at a new, negative level.

Given that capital remains the same, output falls are only due to a decrease in the value of oil. As shown in table 4.10, in the initial year of the simulation, Russian GDP falls about 10 percent below its baseline level. Within a century, the Russian economy adapts and by 2080, Russia's GDP is 4 percent above its baseline level. This reflects increased labor supply as Russians respond to the loss in income associated with their now higher taxes and the fact that oil reserves exhaust, effectively reducing output even in the baseline scenario.

The decline in oil revenues plays an important role in this scenario. As in previous scenario, the lower market value of fossil-fuel assets leads to less crowding out of capital investment. This new capital dynamic is clear from the results shown in table 4.10. In 2013 the capital stock is the same as in the baseline, however a few years later, in 2017, capital stock is already 8.6 percent higher than baseline levels, and by 2100, 33 percent higher. This increase in capital stocks above the baseline is also partly due to Russian savers, who would have otherwise invested abroad, purchasing domestic capitals.

To finance government spending while keeping the debt-to-GDP ratio fixed, taxes must be increased. This hurts multiple generations. However, because the government has a large new source of revenue, and because private incomes are reduced by a smaller amount, taxation rates need to rise by a smaller amount than in the previous scenario. Of all taxes, the consumption tax increases the most. It increases to about 4 times its baseline level. This continues to be a main factor in the immiseration of the Russian elderly. In order to make up for the fall in oil revenues, the average tax rate burden increases 27 percent relative to the baseline. Tax rates remain at this elevated level through most of the century. In addition to the tax burden, workers see their wages fall immediately after moving to autarky, mainly due to the expansion of the effective labor supply. However, by 2030 wages recover and because capital stock continues to increase, future wages outpace those from the baseline. For instance, in 2050 low-skilled workers' wages are 5.7 percent higher than baseline and by the end of the century they are 10.8 percent higher. Similarly, wages of the high-skilled workers are 5.4 and 10.2 percent higher than baseline in 2050 and 2100, respectively.

How much of the negative effect should be attributed to sanctions and how much to the lower oil revenues? Table 4.14 includes a comparison of our welfare measure for both. In absence of an oil shock, the model only registers about 10 percent of the observed loss in welfare. If Russia had not experienced the sharp fall of oil revenues, GDP would have declined about 10 percent (relative to baseline) due to the limited trade opportunities. The abundance of oil-related assets reduces the capital stock accumulation but keeps the interest rates relatively stable around 5 percent. Because oil revenues remain relatively high, taxes barely increase, allowing households to consume enough and reducing all generational welfare losses.

Finally, do welfare effects improve those seen in the capital flight scenario? Table 4.14 says it does. While all Russians alive in 2013 are hurt by the decline in the fossil fuel price, the elderly are affected the most. In fact, cohorts born between 1940 and 1960 see their utility diminished between 25 and 40 percent. Under this scenario, generations born around 2020 seem to be unaffected. Why are the elderly affected the most? This is because the older generations face higher consumption taxes and do not have enough time to adjust their labor supply and saving as younger generations do. As in the capital flight scenario, since oil resources exhaust, future generations show little to no negative effects once relative to the baseline. However, when contrasting the 1980-2050 generation's welfare in the two scenarios, the best scenario occurs under asset seizure, as negative effects are reduced by half. However, for those generations born between 1940 and 1970 their lives as retirees will not be as graceful as in the capital flight scenario. In fact they will experience a utility worsening of at least 50 percent.

A complementary approach to studying long-lasting sanctions is to consider their detrimental effects on productivity. The literature has registered the multiple ways that trade benefits a country via spillovers that enhance productivity. In order to exemplify how sanctions may render better outcomes, this chapter expands the previous scenario with an initial fall of labor productivity, followed by a slower catch-up rate. Table 4.11 shows the impact on GDP, capital stocks, and labor supply resulting from this simulation. Capital stock closely follows he transition path of the case of government seizure of assets. However, the levels are slightly lower. Labor supply dynamics are also nearly unchanged. Together with the slower capital accumulation, they lead to lower GDP. Immediately after moving into autarky, GDP remains as in the previous scenario. However, by 2030, the lower productivity has already impacted output which is about 5 percent lower than in the government seizure standard scenario. In terms of welfare, the situation of generations born between 1940 and 1980 do not worsen since they no longer work when the shock occurs. However, for all other cohorts employed when sanctions are imposed, their utility worsens about 50 percent compared to the previous scenario. Long-lasting sanctions have long-lasting effects, as the last generations with welfare losses are those born in 2040.

4.6 Conclusion

This paper simulates the economic transition of Russia as a member of a six-region global economy, and under autarky. Motivated by recent events, the model focuses on the impact that sanctions may have on the Russian economy.

Under the free trade baseline, the model predicts vast changes over the next hundred years. It projects how the economic ascendancy of China and India transforms the other regions into small players in the global economic stage. While the Russian, EU, and U.S. economies grow at very similar rates, these rates are dramatically lower than those of China and India. In 2100, these two regions produce almost two-thirds of total seven-region output -up from one-third in 2013. Thanks to its remarkably large projected decline in population, the combined Japanese/Korean economy is unable to keep up even with the Western economies.

Autarky is shown to be severely negative for currently living Russians. Table 4.14 summarizes our results. The depth of the detrimental effects are conditional on what to extent energy revenues are impacted, whether there are additional impacts on productivity, and whether Russia seizes foreign assets. Under the most punishing form of autarky, when a full withdrawal of foreign capital occurs and Russian oil loses three quarters of its value, stocks of capital are reduced to 23 percent of their baseline value. This impacts GDP severely, inducing large reductions in welfare. The impact would be especially large for generations born from 1940 to 1980.

In contrast, if the government responds by seizing foreign assets located in Russia, GDP will only fall by 10 percent (so long as labor productivity is not directly impacted). This is mostly due to a reduction in the value of Russian oil. Even under this more benign scenario, older generations still suffer as their tax burden increases and they have no time to adapt or to work to increase their income.

Russia already faces major fiscal challenges over the course of the century. Public expenditures associated with population aging require massive tax hikes. But fossil-fuel depletion and the potential for permanently lower fossil fuel prices make Russia's fiscal finances particularly precarious. Under almost all scenarios, autarky makes generations being born today or earlier even worse off. The generation being born today is better off (if only slightly) in the most benign scenario, with government capital seizure and no effect on oil revenues. This is in part because of increased capital accumulation as Russian savers are forced to invest their funds domestically.

An increase in the severity of sanctions therefore will almost certainly worsen Russia's economic conditions. Brinkmanship is unpleasant in all its forms. We therefore hope policymakers, especially in Russia, will take note of the potentially severe consequences of further economic escalation, and achieve a just and lasting peace.

4.7 Annex: Tables and Charts

Figure 4·4: High-Skilled Effective Labor Supply

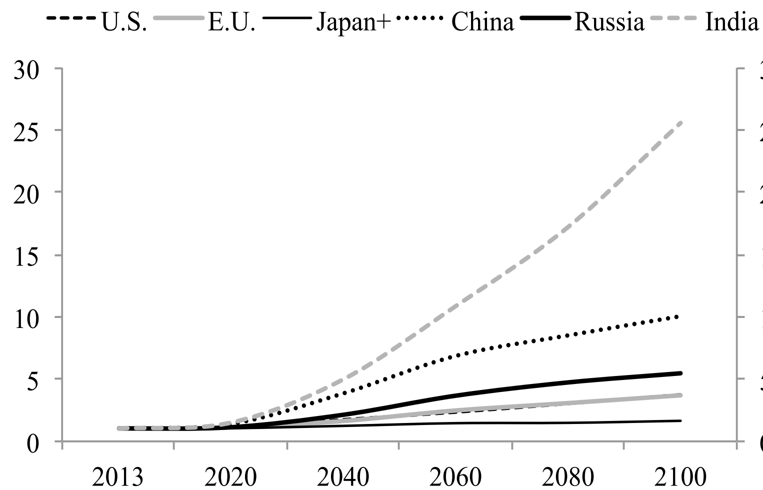


Figure 4·5: Low-Skilled Effective Labor Supply

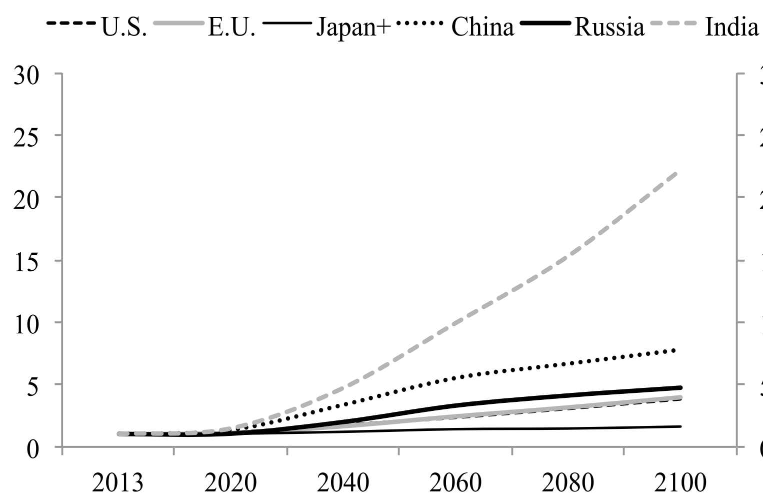


Table 4.6: The year 2013 of the baseline path

	Model						Actual					
	U.S.	EU	Japan+	China	India	Russia	U.S.	EU	Japan+	China	India	Russia
Gross domestic product (PPP) as share of U.S.	100.0	104.0	37.8	97.7	39.8	20.1	100.0	104.2	37.9	96.3	40.4	20.8
Private consumption as share of GDP	68.2	57.4	59.1	35.4	59.3	53.5	68.6	57.5	58.0	34.0	61.0	52.8
Government consumption as share of GDP[a]	19.5	21.8	19.4	19.6	16.6	24.4	19.2	23.2	19.0	19.1	16.5	24.3
Fossil fuel rents as share of GDP	1.0	0.3	0.1	2.8	2.6	18.1	1.0	0.3	0.0	3.4	2.9	17.1
Government revenues as share of GDP												
Total tax revenues	27.9	27.8	29.3	23.3	20.1	18.9	21.0	22.7	26.2	20.9	17.5	18.2
Consumption tax	13.0	14.3	11.4	18.3	13.5	12.6	9.8	11.7	13.7	15.7	11.7	11.3
Corporate tax	3.4	3.0	5.6	3.6	4.2	2.1	2.4	2.7	5.5	4.1	3.7	3.1
Income tax	11.5	10.4	12.3	1.4	2.4	4.2	8.8	8.3	7.0	1.1	2.0	3.8
Non-tax revenues	6.2	14.8	6.2	1.5	2.2	19.2	6.8	17.3	2.6	1.5	2.3	18.4
Social insurance revenues	5.9	14.7	6.2	1.5	2.0	7.5	5.7	15.8	0.5	1.5	1.9	7.2
Other	0.3	0.1	0.0	0.0	0.2	11.7	1.1	1.5	2.1	0.0	0.4	11.1
Government expenditures as share of GDP												
Health	8.0	7.5	8.4	1.5	1.0	3.9	7.8	7.9	8.2	1.4	0.9	3.9
Education	5.2	5.4	6.9	4.0	2.8	4.4	5.1	5.7	6.8	3.9	2.8	4.4
Purchases of G&S excl. health and education	6.4	9.0	4.1	14.1	12.8	16.1	6.3	9.6	4.0	13.8	12.8	16.0
Pension benefits	9.1	15.8	6.2	2.8	4.8	9.3	8.5	16.9	6.2	2.6	4.1	8.9
Other transfer benefits	5.2	6.1	8.7	2.4	1.7	3.9	5.1	6.5	8.5	2.4	1.7	3.9
Net payments on debt/assets	0.7	-1.8	1.3	0.2	3.4	0.6	0.6	-2.3	1.8	0.2	4.5	0.7

a: Government consumption is the sum of education, health, and other purchases of goods and services.

Table 4.7: Baseline Simulation Results - Capital and Labor Supplies are Relative to 2013 U.S.

	Year	GDP	Capital Stock	Labor Supply Low Skilled	High Skilled	Corporate Tax	Income Tax	Pension Tax	Consumption Tax
U.S.	2013	1.00	1.00	1.00	1.00	40.00	14.75	19.06	9.22
	2020	1.14	1.12	1.16	1.16	40.00	16.46	21.64	11.08
	2040	1.58	1.35	1.74	1.74	40.00	19.54	27.68	13.43
	2060	2.13	1.83	2.35	2.37	40.00	20.80	31.34	14.99
	2080	2.82	2.50	3.04	3.08	40.00	21.49	34.61	15.63
	2100	3.37	2.83	3.74	3.85	40.00	21.94	35.39	17.17
E.U.	2013	1.04	1.18	0.96	1.03	22.80	13.87	24.99	22.73
	2020	1.14	1.27	1.07	1.15	22.80	14.41	25.58	25.08
	2040	1.58	1.54	1.57	1.71	22.80	15.97	28.09	29.56
	2060	2.36	2.31	2.38	2.52	22.80	16.09	31.38	22.99
	2080	3.03	3.06	2.95	3.26	22.80	15.75	30.31	28.67
	2100	3.60	3.45	3.55	4.10	22.80	15.29	27.74	33.67
Japan+	2013	0.38	0.40	0.37	0.38	35.20	15.38	19.21	9.71
	2020	0.39	0.40	0.39	0.40	35.20	15.68	18.98	10.92
	2040	0.43	0.38	0.46	0.46	35.20	15.40	17.19	14.43
	2060	0.50	0.45	0.54	0.54	35.20	16.04	17.79	13.61
	2080	0.52	0.48	0.55	0.56	35.20	16.77	18.22	15.57
	2100	0.56	0.49	0.61	0.62	35.20	16.87	18.32	16.05
China	2013	0.98	1.07	1.00	0.80	25.00	1.83	51.68	2.42
	2020	1.33	1.43	1.40	1.09	25.00	1.76	46.36	2.48
	2040	3.25	3.12	3.85	2.70	25.00	1.81	39.92	1.92
	2060	5.59	5.39	6.86	4.42	25.00	2.04	41.32	2.46
	2080	6.98	6.95	8.51	5.34	25.00	2.19	39.74	5.29
	2100	7.94	7.52	10.05	6.24	25.00	2.17	39.20	6.09
India	2013	0.40	0.41	0.42	0.33	34.00	3.63	22.80	3.10
	2020	0.58	0.59	0.63	0.49	34.00	3.40	22.64	3.09
	2040	1.74	1.56	2.09	1.56	34.00	3.57	25.94	2.34
	2060	3.73	3.37	4.56	3.28	34.00	4.22	32.80	3.14
	2080	5.96	5.58	7.23	5.05	34.00	4.96	37.90	5.95
	2100	8.48	7.51	10.74	7.33	34.00	5.24	40.05	7.09
Russia	2013	0.20	0.19	0.15	0.16	20.00	6.52	23.52	14.10
	2020	0.22	0.20	0.17	0.17	20.00	7.68	28.13	16.32
	2040	0.35	0.31	0.32	0.32	20.00	9.14	39.61	14.40
	2060	0.57	0.53	0.55	0.53	20.00	10.63	51.93	11.98
	2080	0.73	0.71	0.71	0.66	20.00	11.17	53.86	19.15
	2100	0.78	0.76	0.82	0.76	20.00	12.67	60.49	24.15

Table 4.8: Marginal Products and Factor Payments in the Baseline Transition

Country	Year	Marg. Prod. Capital	Global Int. Rate	Wage Rates Low	Wage Rates High	Marg. Prod. of Labor Low	Marg. Prod. of Labor High
USA	2013	14.36	4.12	1.00	1.58	1.00	1.58
	2020	14.74	4.34	0.99	1.55	0.99	1.55
	2040	16.98	5.69	0.91	1.44	0.91	1.44
	2060	16.95	5.67	0.92	1.43	0.92	1.43
	2080	16.36	5.32	0.94	1.46	0.94	1.46
	2100	17.37	5.92	0.91	1.40	0.91	1.40
EU	2013	12.83	4.12	0.46	0.67	1.09	1.60
	2020	13.13	4.34	0.51	0.75	1.08	1.58
	2040	14.87	5.69	0.86	1.25	1.01	1.47
	2060	14.85	5.67	1.01	1.49	1.01	1.49
	2080	14.39	5.32	1.04	1.48	1.04	1.48
	2100	15.17	5.92	1.03	1.40	1.03	1.40
JAP	2013	13.85	4.12	0.55	0.84	1.03	1.58
	2020	14.20	4.34	0.59	0.90	1.01	1.56
	2040	16.28	5.69	0.82	1.29	0.94	1.46
	2060	16.25	5.67	0.93	1.48	0.93	1.48
	2080	15.70	5.32	0.95	1.50	0.95	1.50
	2100	16.64	5.92	0.93	1.45	0.93	1.45
CH	2013	12.99	4.12	0.09	0.18	0.97	1.91
	2020	13.29	4.34	0.17	0.35	0.95	1.92
	2040	15.09	5.69	0.65	1.46	0.85	1.91
	2060	15.06	5.67	0.82	2.01	0.82	2.01
	2080	14.59	5.32	0.83	2.08	0.83	2.08
	2100	15.40	5.92	0.80	2.03	0.80	2.03
INDIA	2013	13.74	4.12	0.05	0.10	0.94	1.86
	2020	14.08	4.34	0.07	0.15	0.92	1.85
	2040	16.12	5.69	0.22	0.47	0.84	1.77
	2060	16.09	5.67	0.38	0.83	0.83	1.82
	2080	15.55	5.32	0.54	1.21	0.83	1.88
	2100	16.47	5.92	0.67	1.54	0.80	1.85
RUSSIA	2013	12.65	4.12	0.23	0.35	1.08	1.67
	2020	12.93	4.34	0.28	0.44	1.06	1.66
	2040	14.61	5.69	0.60	0.96	0.98	1.58
	2060	14.59	5.67	0.92	1.53	0.97	1.61
	2080	14.14	5.32	0.98	1.66	0.98	1.66
	2100	14.90	5.92	0.95	1.62	0.95	1.62

Note: Measured at age 30 per unit of effective time scaled by the wage of 30 year-old low skilled Americans in 2013. Marginal product of labor is in proportion to U.S. 2013 levels. The wedge between the marginal product of capital and the global interest rate is a function of both the depreciation rate (7.5 percent) and country specific corporate tax rates.

Table 4.9: Autarky With Capital Flight

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Year	GDP	Capital	Labor Supply Low Skill	Labor Supply High Skill	Corporate Tax	Income Tax	Consumption Tax
	% of Baseline				Rate, %		
2013	57.2	23.47	111.43	112.85	20.0	8.2	40.9
2017	64.6	33.94	109.73	111.76	20.0	9.0	43.6
2020	68.2	40.35	109.23	110.66	20.0	9.4	45.3
2025	72.4	46.61	107.62	108.93	20.0	9.8	47.1
2030	74.6	51.06	106.06	107.22	20.0	9.7	47.4
2035	77.7	57.10	104.78	105.81	20.0	9.7	47.9
2040	81.4	64.67	104.10	104.74	20.0	9.8	48.7
2050	86.2	74.11	102.69	103.00	20.0	10.4	52.7
2060	87.5	77.09	100.79	100.67	20.0	10.6	54.7
2080	93.8	92.88	99.88	99.60	20.0	11.5	56.4
2100	98.6	95.78	100.00	99.88	20.0	12.3	59.6

Table 4.10: Autarky With Capital Seizure

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Year	GDP	Capital	Labor Supply Low Skill	Labor Supply High Skill	Corporate Tax	Income Tax	Consumption Tax
	% of Baseline				Rate, %		
2013	90.5	100.00	108.57	107.26	20.0	8.8	39.0
2017	92.3	108.60	106.49	106.42	20.0	9.7	43.3
2020	93.5	112.28	105.64	105.58	20.0	10.6	47.3
2025	94.6	111.55	104.48	104.46	20.0	11.1	50.0
2030	94.5	110.28	103.03	103.04	20.0	11.1	50.5
2035	95.8	111.67	102.23	102.26	20.0	10.9	49.8
2040	97.7	116.52	101.91	101.67	20.0	10.7	48.9
2050	99.8	117.86	101.04	101.07	20.0	11.2	51.8
2060	99.5	114.38	100.00	100.17	20.0	11.0	52.3
2080	104.0	127.72	99.14	99.34	20.0	11.7	54.0
2100	110.2	133.49	99.47	100.00	20.0	11.8	53.3

Table 4.11: Autarky With Capital Seizure and Productivity Impacts

Year	GDP	Capital	Labor Supply Low Skill	Labor Supply High Skill	Corporate Tax	Income Tax	Consumption Tax
	% of Baseline				Rate, %		
2013	90.0	100.00	108.00	107.26	20.0	8.7	38.5
2017	91.9	107.69	105.95	105.88	20.0	9.6	42.6
2020	92.6	110.96	104.10	104.06	20.0	10.5	46.4
2025	92.5	109.96	101.79	101.79	20.0	11.0	48.9
2030	91.2	107.45	98.86	98.86	20.0	11.0	49.3
2035	91.3	107.57	96.18	96.77	20.0	10.8	48.6
2040	91.7	110.26	94.54	94.71	20.0	10.6	47.8
2050	91.4	108.48	91.93	92.49	20.0	11.1	50.7
2060	90.5	103.51	90.79	91.47	20.0	11.0	51.9
2080	98.8	118.85	94.94	95.63	20.0	11.7	54.1
2100	110.0	133.02	99.47	100.23	20.0	11.8	53.9

Table 4.12: Autarky With Capital Flight and No Oil Shock

Year	GDP	Capital	Labor Supply Low Skill	Labor Supply High Skill	Corporate Tax	Income Tax	Consumption Tax
	% of Baseline				Rate, %		
2013	60.2	13.15	105.71	107.26	20.0	2.7	11.4
2017	71.3	27.15	104.86	106.95	20.0	4.2	17.2
2020	76.5	35.96	104.62	105.58	20.0	5.1	20.6
2025	81.2	45.42	103.14	104.02	20.0	6.1	25.0
2030	83.5	52.48	101.89	102.28	20.0	6.6	28.0
2035	86.1	59.62	100.96	101.29	20.0	7.1	30.8
2040	88.9	68.38	100.55	100.56	20.0	7.6	33.7
2050	92.3	78.35	99.38	99.14	20.0	8.8	40.5
2060	92.3	81.44	97.93	97.32	20.0	9.4	44.8
2080	99.3	100.62	98.52	98.01	20.0	10.8	50.8
2100	99.4	99.06	99.47	99.19	20.0	12.4	59.4

Table 4.13: Autarky With Capital Seizure and No Oil Shock

Year	GDP	Capital	Labor Supply Low Skill	Labor Supply High Skill	Corporate Tax	Income Tax	Consumption Tax
	% of Baseline				Rate, %		
2013	90.0	63.38	106.29	105.03	20.0	1.1	3.6
2017	95.2	79.64	103.78	103.74	20.0	3.7	13.1
2020	97.7	89.47	103.08	102.03	20.0	5.3	19.5
2025	100.4	98.41	101.35	100.89	20.0	6.9	26.2
2030	100.7	104.26	100.00	99.24	20.0	7.8	30.6
2035	102.3	110.41	99.04	98.39	20.0	8.3	33.4
2040	104.0	118.23	98.63	98.05	20.0	8.6	35.3
2050	105.4	122.99	98.34	97.64	20.0	9.7	41.5
2060	104.4	120.40	97.62	96.99	20.0	10.0	44.8
2080	109.3	137.70	97.65	97.48	20.0	11.8	53.3
2100	110.8	137.12	98.93	99.42	20.0	12.0	53.7

Table 4.14: Welfare Effects on Russia by Scenario

Birth Year	Foreign Capital Flight		Government Seize		Productivity Slowdown		Foreign Capital Flight No Oil Shock		Government Seize No Oil Shock	
	Low	High	Low	High	Low	High	Low	High	Low	High
1940	-25.45	-21.24	-41.74	-35.42	-41.51	-35.15	-2.34	0.08	-27.04	-20.50
1960	-20.07	-18.56	-30.75	-25.39	-30.68	-25.26	-1.58	-2.58	-19.86	-14.81
1980	-29.23	-27.86	-17.77	-14.68	-17.63	-14.54	-16.08	-15.78	-7.15	-4.36
2000	-20.70	-19.64	-7.98	-6.86	-12.07	-10.84	-9.32	-8.90	2.05	2.67
2010	-12.48	-11.48	-4.56	-3.91	-10.85	-9.85	-2.84	-2.54	3.19	3.31
2020	-7.38	-6.55	-1.50	-1.33	-8.96	-8.23	-0.01	0.19	4.52	4.17
2030	-3.96	-3.35	0.71	0.45	-7.52	-7.03	1.73	1.79	5.46	4.72
2040	-1.82	-1.37	2.06	1.47	-4.56	-4.46	2.45	2.41	5.55	4.54
2050	-0.16	0.09	3.79	2.82	3.54	2.41	3.05	2.91	6.33	5.05
2060	0.89	1.04	5.73	4.38	5.94	4.40	2.90	2.81	7.26	5.73
2070	1.24	1.43	6.66	5.13	7.25	5.53	2.07	2.16	7.11	5.55
2080	0.85	1.23	7.22	5.69	7.96	6.28	1.15	1.49	7.32	5.80
2090	0.55	1.11	7.90	6.39	8.37	6.78	0.54	1.11	7.82	6.34
2100	0.75	1.45	8.51	7.02	8.75	7.22	0.63	1.34	8.38	6.91

Table 4.15: Russian Wages Low Skill in the Baseline and Autarky Scenarios
(Index, Baseline 2013 = 1)

Year	Baseline	Foreign Capital Flight	Government Seize	Productivity Slowdown
2013	1.00	0.58	0.97	0.92
2017	1.22	0.81	1.23	1.14
2020	1.38	0.98	1.41	1.29
2025	1.64	1.23	1.68	1.51
2030	1.88	1.46	1.92	1.71
2035	2.10	1.70	2.17	1.92
2040	2.32	1.97	2.43	2.14
2045	2.55	2.24	2.70	2.36
2050	2.80	2.50	2.96	2.56
2060	3.02	2.75	3.17	2.99
2068	3.04	2.87	3.25	3.23
2080	3.05	2.97	3.33	3.30
2100	2.96	2.91	3.28	3.28

Table 4.16: Russian Wages High Skill in the Baseline and Autarky Scenarios
(Index, Baseline 2013 = 1)

Year	Baseline	Foreign Capital Flight	Government Seize	Productivity Slowdown
2013	1.00	0.57	0.98	0.93
2017	1.23	0.81	1.24	1.15
2020	1.39	0.97	1.42	1.30
2025	1.66	1.23	1.70	1.53
2030	1.92	1.48	1.97	1.75
2035	2.17	1.74	2.24	1.97
2040	2.42	2.03	2.53	2.22
2045	2.68	2.34	2.83	2.46
2050	2.96	2.63	3.12	2.69
2060	3.24	2.95	3.40	3.18
2068	3.29	3.11	3.51	3.47
2080	3.33	3.26	3.64	3.59
2100	3.25	3.21	3.59	3.58

Table 4.17: Russian Average Tax Rate in the Baseline and Autarky Scenarios
(Percentage, %)

Year	Baseline	Foreign Capital Flight	Government Seize	Productivity Slowdown
2013	39.6	59.0	50.3	50.0
2017	43.6	60.7	54.6	54.3
2020	45.9	61.4	58.0	57.7
2025	48.2	60.5	59.3	59.0
2030	49.5	58.7	59.2	59.0
2035	50.6	57.4	58.2	58.3
2040	51.9	57.0	57.7	58.1
2045	53.7	57.3	58.3	58.9
2050	55.0	57.2	58.5	59.1
2060	56.8	57.0	57.5	58.1
2068	59.6	59.5	59.2	59.4
2080	65.3	65.4	65.7	65.0
2100	74.6	73.0	70.3	68.6

Table 4.18: Russian Government Spending in the Baseline and Autarky Scenarios
(Percentage of GDP, %)

Year	Baseline	Foreign Capital Flight	Government Seize	Productivity Slowdown	Foreign Capital Flight No Oil	Government Seize No Oil
2013	32.5	43.7	38.6	38.7	36.4	34.2
2017	34.8	45.0	40.9	41.0	38.0	36.4
2020	36.0	45.7	42.3	42.4	38.9	37.6
2025	36.5	45.1	42.8	43.0	39.0	38.3
2030	35.9	43.4	42.0	42.4	38.1	37.9
2035	35.5	41.9	41.3	41.8	37.4	37.6
2040	35.9	41.2	41.3	42.0	37.2	37.8
2045	36.7	41.2	41.9	42.7	37.7	38.7
2050	37.0	41.1	42.0	42.9	38.0	39.1
2060	36.7	40.2	41.2	41.7	37.9	39.0
2070	39.6	42.1	43.2	43.2	40.1	41.2
2080	44.1	45.8	46.8	46.1	43.8	44.9
2090	49.0	48.8	49.4	48.1	48.6	49.2
2100	51.6	51.9	52.2	50.7	51.9	52.2

Table 4.19: Russian Interest Rates in the Baseline and Autarky Scenarios
(Percentage, %)

Year	Baseline	Foreign Capital Flight	Government Seize	Productivity Slowdown	Foreign Capital Flight No Oil	Government Seize No Oil
2013	4.1	22.0	4.7	4.6	33.3	8.1
2017	4.2	15.9	4.1	4.1	18.7	6.1
2020	4.3	13.8	4.0	3.9	14.8	5.3
2025	4.6	12.3	4.1	4.1	12.1	4.8
2030	4.9	11.6	4.5	4.4	10.9	4.6
2035	5.3	10.9	4.7	4.6	10.0	4.5
2040	5.7	10.0	4.7	4.6	9.0	4.4
2045	5.9	9.2	4.7	4.6	8.3	4.3
2050	5.9	8.7	4.8	4.7	7.9	4.3
2060	5.7	7.9	4.7	4.7	7.1	4.2
2070	5.4	6.5	4.0	4.1	5.9	3.5
2080	5.3	5.8	3.6	3.8	5.1	3.0
2090	5.6	5.9	3.7	3.9	5.4	3.3
2100	5.9	6.2	3.9	3.9	5.9	3.7

Table 4.20: Russian Household Consumption in the Baseline and Autarky Scenarios
(Percentage of GDP, %)

Year	Baseline	Foreign Capital Flight	Government Seize	Productivity Slowdown	Foreign Capital Flight No Oil	Government Seize No Oil
2013	53.5	53.4	44.3	44.5	61.3	51.5
2017	53.6	52.8	44.4	44.6	59.3	50.3
2020	53.3	52.7	44.3	44.6	58.6	49.5
2025	51.4	52.2	43.9	44.3	57.3	48.2
2030	49.1	51.4	43.6	44.1	55.7	47.1
2035	47.7	50.5	43.5	44.0	54.2	46.4
2040	47.3	49.9	43.7	44.2	53.0	46.1
2045	47.0	49.3	43.6	44.2	52.0	45.7
2050	45.8	48.5	43.1	43.7	50.8	44.9
2060	42.9	47.1	42.1	42.5	48.8	43.4
2070	43.5	47.3	42.7	42.7	48.2	43.3
2080	45.2	48.2	43.6	43.3	47.8	43.0
2090	47.6	48.9	44.3	43.7	49.1	44.5
2100	48.7	49.9	45.3	44.5	50.0	45.5

Chapter 5

Conclusions

5.1 Robots are Us: Some Economics of Human Behavior

Will smart machines, which are rapidly replacing workers in a wide range of jobs, produce economic misery or prosperity? Our two-period, OLG model admits both outcomes. But it does firmly predict three things - a long-run decline in labor share of income (which appears underway in OECD members), tech-booms followed by tech-busts, and a growing dependency of current output on past software investment.

The obvious policy for producing a win-win from higher code retention is taxing those workers who benefit from this technological breakthrough and saving the proceeds. This will keep the capital stock from falling and provide a fund to pay workers a basic stipend as their wages decline through time. Other policies for managing the rise of smart machines may backfire. For example, restricting labor supply may reduce total labor income. While this may temporarily raise wages, it will also reduce investment and the long-term capital formation on which long-term wages strongly depend. Another example is mandating that all code be open source. This policy removes one mechanism by which capital is crowded out, but it leads firms to free ride on public code rather than hire new coders. This reduces wages, saving, and, in time, the capital stock.

Our simple model illustrates the range of things that smart machines can do for us and to us. Its central message is disturbing. Absent appropriate fiscal policy that redistributes from winners to losers, smart machines can mean long-term misery for all.

5.2 Robots: Curse or Blessing

The rise of the robots is already creating major disruption in labor markets, essentially turning production processes more capital intensive. When robots are close substitutes for production by labor and machinery, the demand for labor is likely to decline, threatening a decline of wages, saving, and economic well-being of current and future generations. We have qualified that intuition, however, in two important ways. First, government redistribution can ensure that a pure productivity improvement raises well-being of all generations. In the example shown in the paper, government taxes the capital owned by retirees and distributing the proceeds to young workers. Second, to the extent that workers produce outputs that are imperfect substitutes of the outputs of robots, workers will experience a rise in demand for their products, and this can result in a virtuous circle of rising wages, savings, and production, producing the open-ended constant growth of an AK model.

5.3 Can Russia Survive Economic Sanctions?

This paper simulates the economic transition of Russia as a member of a six-region global economy, and under autarky. Motivated by recent events, the model focuses on the impact that sanctions may have on the Russian economy.

Under the free trade baseline, the model predicts vast changes over the next hundred years. It projects how the economic ascendancy of China and India transforms the other regions into small players in the global economic stage. While the Russian, EU, and U.S. economies grow at very similar rates, these rates are dramatically lower than those of China and India. In 2100, these two regions produce almost two-thirds of total seven-region output -up from one-third in 2013. Thanks to its remarkably large projected decline in population, the combined Japanese/Korean economy is unable to keep up even with the Western economies.

Autarky is shown to be severely negative for currently living Russians. Table 4.14 summarizes our results. The depth of the detrimental effects are conditional on what to extent energy revenues are impacted, whether there are additional impacts on productivity, and whether Russia seizes foreign assets. Under the most punishing form of autarky, when a full withdrawal of foreign capital occurs and Russian oil loses three quarters of its value, stocks of capital are reduced to 23 percent of their baseline value. This impacts GDP severely, inducing large reductions in welfare. The impact would be especially large for generations born from 1940 to 1980.

In contrast, if the government responds by seizing foreign assets located in Russia, GDP will only fall by 10 percent (so long as labor productivity is not directly impacted). This is mostly due to a reduction in the value of Russian oil. Even under this more benign scenario, older generations still suffer as their tax burden increases and they have no time to adapt or to work to increase their income.

Russia already faces major fiscal challenges over the course of the century. Public expenditures associated with population aging require massive tax hikes. But fossil-fuel depletion and the potential for permanently lower fossil fuel prices make Russia's fiscal finances particularly precarious. Under almost all scenarios, autarky makes generations being born today or earlier even worse off. The generation being born today is better off (if only slightly) in the most benign scenario, with government capital seizure and no effect on oil revues. This is in part because of increased capital accumulation as Russian savers are forced to invest their funds domestically.

An increase in the severity of sanctions therefore will almost certainly worsen

Russia's economic conditions. Brinkmanship is unpleasant in all its forms. We therefore hope policymakers, especially in Russia, will take note of the potentially severe consequences of further economic escalation, and achieve a just and lasting peace.

Notes

[1]with Seth G. Benzell, Laurence J. Kotlikoff, and Jeffrey D. Sachs

[2]Astro Teller, Googles Director of Moonshots, discusses in (Madrigal, 2014) the importance of this work to Google's current projects:

> *Many of Googles famously computation driven projects –like the creation of Google Maps– employed literally thousands of people to supervise and correct automatic systems. It is one of Googles open secrets that they deploy human intelligence as a catalyst. Instead of programming in that last little bit of reliability, the final 1 or 0.1 or 0.01 percent, they can deploy a bit of cheap human brainpower. And over time, the humans work themselves out of jobs by teaching the machines how to act. "When the human says, 'Here's the right thing to do,' that becomes something we can bake into the system and that will happen slightly less often in the future," Teller said.*

[3]This figure is the share of wages paid to workers in Computer or Mathematical Occupations in the May 2013 NAICS Occupational Employment and Wage Estimates.

[4]A code retention rate below 1, which we assume, ensures balanced growth.

[5]Balanced growth is ruled out Cobb-Douglas utility and an ultimate limit on inputs to the service sector.

[6]As discussed below, this reflects the adjustment of the relative price of the low-tech service good.

[7]The rate of code depreciation in the economy as a whole is unclear. Information technology systems that used to be perfectly adequate are continuously updated and amended to deal with new problems or interface with new complements. A depreciation rate of 30 percent over a 30-40 year generation is assumed in many of our simulations. This corresponds to a typical company needing to replace approximately 1 percent of its code base every year to maintain the same level of output.

In calculating depreciation the IRS allows for a 3 year useful lifespan for licensed software. For software developed in house or purchased bespoke software, costs must be amortized over a 15 year period (as a section 197 intangible). Software which is bundled with hardware depreciates at the rate of the hardware. On the other hand, many programs created over 50 years ago are still in use, such as those written for older nuclear reactors.

[8]To understand this production function consider a firm which provides the service of 'making good chess moves'. Better chess playing smart machines are, in part, distinguished by how many game trees they can investigate and the level of sophistication with which they evaluate board positions and determine which sequences of moves to spend more computational time considering. Therefore, our firm can improve the quality of its output (the chess move it chooses) by increasing either of its inputs. It can either increase the quality of its chess program (increasing its efficiency units of code) or devote more computing time to investigating possible moves and counter-moves (rent more capital). While the logic of decreasing marginal returns to an input seems to hold for production of this type, this does not imply any specific structure on overall returns to scale. Here we restrict our attention to constant returns to scale production.

[9]This selfish OLG framework is, of course, essential for good times to produce bad times. Were agents altruistic they would spread the economic gains from the rise in code retention across all generations via gifts and bequests. But the micro evidence against operational intergenerational altruism is substantial and striking. See, for example, (Altonji et al., 1992; Altonji et al., 1997), (Hayashi et al., 1996), and (Abel and Kotlikoff, 1994). This is true notwithstanding the popularity of models with infinitely-lived agents. Adding additional periods of life would not impact our qualitative results.

[10]With population- or labor augmenting technological change, capital per unit of code would be the key steady-state variable.

[11]There are two solutions depending on whether $1+f_K(k) > \delta$ or not. However, only the former condition permits a positive price of code.

[12]For the Cobb-Douglas case, we also have

$$\frac{dk}{d\delta} = -\frac{aD_y k^{\alpha-1} + \alpha(1-\alpha)[D_y k^{\alpha-1}]^2 - b}{2\alpha(1-\alpha)cD_y^2 k^{2\alpha-3} + (1-\alpha)eD_y k^{\alpha-2}}$$

where $a = [1 + \frac{(1-\kappa)(1-2\alpha)}{\phi}]$, $b = \frac{(1-\kappa)}{\phi}$, $c = 1 - (\alpha + \delta(1-\alpha))$, and $e = (1-\delta)(1-\alpha b) - b(1-(1-\alpha)\delta)$. While this derivative is rather unwieldy, it easy to come up with parameter values such that the derivative is of either sign. This underlies our main point, namely that a higher code retention rate can reduce long-run capital intensity.

[13]Throughout, unless otherwise noted, national income, wages, and prices are all reported in real terms. The price index used is a geometric mean of the relative price of goods and services. The weights used are their corresponding shares in consumption. The price index is $\Pi_t = q_t^{\frac{S_{y,t}+S_{o,t}}{C_{y,t}+C_{o,t}}}$

[14]It is also unclear how to choose reasonable initial values for κ, but this has little impact on the dynamic effect of code accumulation. Immiseration is still possible for high κ.

[15]Consider a doubling in H. This will double H_Y in the $\delta = 0$ economy. But if H_Y also doubles along the entire transition path, the path of k will remain unchanged. One can see this by combining the equation for market-clearing in capital with that for market-clearing in code. This, of course, requires the path of H_S be twice as large as well. But this outcome as well as a doubling of path of q_t is implied by equation 16. This k-path invariance to initial levels of H and G is somewhat surprising and suggests that transforming more low-skilled into-high-skilled workers may have less impact on the economy than one might have thought. Still, such a policy, if enacted before the rise in delta, would lower the real wages of skilled workers (their wages valued in capital wouldn't change, but the higher price of S would lower their real wage. It would also improve the relative lot of those who remain unskilled workers since their wage measured in units of capital will rise thanks to the higher marginal revenue of their labor. Additional effects would arise were H or G to vary once delta had risen and the economy was in transition. In this case, the k path would temporarily fall making code and coding less valuable. However, in the long run, the real wages of each type of worker are independent of such transition effects on the

path of k.

[16]This, and the previous result, can both be shown analytically.

[17]If the number of firms is fixed due to oligopilization of the industry, equation 35 would not hold, in which case the marginal productivity of code would again decrease as it accumulates.

[18]In what follows, we consider only equilibria in which high-tech workers work in both sectors. If the public endowment is large enough in a period, goods firms will require no new code.

[19]$Y''(\alpha) = B\frac{A}{K}^{\alpha}(log(A) - log(K))^2$ must always be positive for K and A greater than zero

[20]There are other models than ours that deliver this conclusion. (Karabarbounis and Neiman, 2014) attribute the decline to capital accumulation and their finding of gross substitutability between capital and labor. Rather than capital abundance, (Rognlie, 2016) argues that the decrease in the labor share is due to property scarcity. He attributes the decline in labors' share to an increase in property values and imputed rents.

[21]National income is measured at producer prices.

[22] These numbers are likely underestimates of the increasing importance of programmers, scientists and engineers in the economy. Software is decomposed in NIPA table 2.1 into own account, prepackaged, and custom software. The true value of prepackaged software in the economy is likely undercounted because it is often pirated. It is also often free or sold at a discount in order to cross subsidize some other product or subscription ((Parker and Van Alstyne, 2005). BEA estimates of firms internal creation of their own software are based on very conservative estimates about the share of programmers who are developing new code (rather than maintaining old code) and the rate at which the software stock decays.

[23]US Corporate intangible assets are calculated as US corporate equity less corporate net worth from Federal Reserve series Z.1.

[24] course, an alternative explanation would be the accumulation of unmeasured

intangible assets (i.e. the true average product of capital would be much lower if all capital were included). Barkai argues that the stock of intangible assets needed to explain the wedge between the observed average product of capital and its marginal cost is implausibly large. The level of intangible assets in 2014 would need to be 42 Trillion (or 54% of U.S. wealth) in order to explain the discrepancy. However, an extremely rapid increase of the share of intangibles in total assets is a phenomena implied by our model.

[25]Capital-hours ratio; BLS multifactor productivity series, Table PG-2-3. Records date back to 1949.

[26]with Seth G. Benzell and Jeffrey D. Sachs

[27]This section draws on (Benzell et al., 2015).

[28]On the other hand, a reduction in long-run national consumption can only occur if Θ increases above 1. This is because the golden rule (long-run consumption maximizing) level of saving, given constant L and 100 percent depreciation is that which brings long-run interest rates equal to 1. In cases where Θ increases from a level below 1 to a level closer to but still below 1, long-run consumption will increase although welfare may decrease.

[29]This is an important assumption. We do not have a strong intuition about whether technological innovations will shift consumption demand towards or away from goods that are relatively labor intensive. Good arguments can be made for both perspectives. If demand does indeed shift towards robotic goods, then our immiserizing mechanism will be amplified and vice versa.

[30]$\tilde{C} = \phi\beta\ln(\beta\phi) + \phi(1-\beta)\ln([1-\beta]\phi) + (1-\phi)\beta\ln(\beta) + (1-\phi)(1-\beta)\ln(1-\beta) + (1-\beta)(\frac{1-\epsilon}{1-\alpha}\ln(\alpha D_{X,t}) - \ln(\epsilon D_{Y,t}) + (1-\epsilon)\ln(\frac{\epsilon[1-\alpha]}{\alpha[1-\epsilon]})) + \phi\ln(\frac{1-\epsilon}{\epsilon}) + \frac{\phi}{1-\epsilon}\ln(\epsilon D_{X,t})$

[31]with Seth G. Benzell

[32]Chapter 6

[33](Doxey, 1982),(Bayard et al., 1983)

[34]Note that assuming a higher rate of technical progress is isomorphic to assuming

the economy has more agents with the same endowment of time on all dimensions except welfare.

[35]As shown in (Hagist et al., 2009), this is a rather conservative assumption concerning future growth in benefit levels.

[36]This section draws from (Fehr et al., 2013)

[37]The main source for population data for all regions apart from Russia's is the medium variant of the United Nations population projections (UNPD, 2014). Demographic data for Russia is based on the average of the UNPD and Rosstat's (the Russian Federal State Statistical Service) projections.

[38]The World Bank uses SSA (2010) as source.

[39]As comprised by the 6 regions modeled

[40]For example: China's value of GDP in 2100 indicates that its economy is 7.94 times larger than the U.S. economy in 2013

[41]For instance, in Japan, population falls by roughly 70 million people between 2013 and 2100. India's population, in contrast, rises by over 400 million.

[42]General productivity growth -the 1 percent growth in the time endowment discussed above -would, by itself, raise global GDP, but only by a factor of 2.

[43]The actual values for China are 10 and 7.8 for low and high-skilled workers, respectively. For Russia, the corresponding values are 5.4 and 4.7

[44]Specifically, we add the income tax and the social security tax rate to $\frac{\eta}{1+\eta}$ where η is the consumption tax rate

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