An Elementary Theory of Global Supply Chains

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Motivation

The rise of vertical specialization

- Most production processes consist of many sequential stages
  - Production of pins in late eighteenth century England
  - Production of tee-shirts, cars, computers, and semi-conductors today
- But production processes today increasingly involve vertical supply chains spanning multiple countries, with each country specializing in particular stages of a good's production sequence
  - This is what Hummels et al. (2001) refer to as "vertical specialization"

Motivation

The consequences of vertical specialization

- This global phenomenon has attracted a lot of attention among policy makers, business leaders, and trade economists alike
- On the academic side of this debate:
  How does the fragmentation of production processes across borders affect the volume, pattern, and consequences of international trade?
- Here, first look at a distinct, but equally important question:
  How does vertical specialization shape "interdependence of nations?"

This Paper

An elementary theory of global supply chains

- A simple trade model with sequential production:
  - Multiple countries, one factor of production (labor), and one final good
  - Production of final good requires a continuum of intermediate stages
  - Each stage uses labor and intermediate good from previous stage
  - Production is subject to mistakes (Sobel 1992, Kremer 1993)
- Key simplifications:
  - Intermediate goods only differ in the order in which they are performed
  - Countries only differ in terms of failure rate
  - All goods are freely traded

Main Results

Free trade equilibrium

- In spite of arbitrary number of countries, unique free trade equilibrium is characterized by simple system of first-order difference equations
- This system can be solved recursively by:
  1. Determining assignment of countries to stages of production
  2. Computing prices sustaining that allocation as an equilibrium outcome
- Free trade equilibrium always exhibits vertical specialization:
  1. More productive countries, which are less likely to make mistakes, specialize in later stages of production, where mistakes are more costly
  2. Because of sequential production, *absolute productivity differences* are a source of *comparative advantage* between nations
- Cross-sectional predictions are consistent with:
  1. "Linder" stylized facts
  2. Variations in value added to gross exports ratio (Johnson Noguera 10)

Main Results

Comparative statics

- Comprehensive exploration of how technological change, either *global* or *local*, affects different participants of a global supply chain
- Among other things, we show that:
  1. Standardization—uniform decrease in failure rates around the world—can cause welfare loss in rich countries: a strong form of immiserizing growth
  2. Spillover effects are different at the bottom and the top of the chain: monotonic effects at the bottom, but not at the top
- **Broad message:** *Important to model sequential nature of production to understand consequences of technological change in developing and developed countries on trading partners worldwide*

Extensions

1. *Coordination costs*
   - Competitive equilibrium remains Pareto optimal
   - But decrease in coordination costs may lead to "overshooting"
2. *Simultaneous production and assembly*
   - Poorest countries specialize in assembly
   - Richest countries specialize in later stages of most complex parts
3. *Imperfect observability of mistakes*
   - Countries with better "quality control" specialize in the earlier stages
4. *General production functions*
   - Provide sufficient conditions s.t. pattern of specialization still holds

Related Literature

- Hierarchies in closed-economy (and mostly partial-equilibrium) models
  - Lucas (1978), Rosen (1982), Sobel (1992), Kremer (1993), Garicano (2000) Garicano Rossi-Hansberg (2006)
- Assignment and matching models in an international context
  - Grossman and Maggi (2000), Grossman (2004), Yeaple (2005), Ohnsorge Trefler (2007), Blanchard Willmann (2010), Nocke Yeaple (2008), Costinot (2009), Costinot Vogel (2010)
- Empirical literature on the importance of vertical specialization
  - Hummels, Rappoport, Yi (1998), Hummels, Ishii, Yi (2001), Hanson, Mataloni, Slaughter (2005), and Johnson Noguera (2010)
- Theoretical literature on fragmentation
  - Dixit Grossman (1982), Sanyal (1983), Yi (2003, 2010), Harms, Lorz, Urban (2009), and Baldwin Venables (2010)

Roadmap of the Talk

1. Basic Environment
2. Free Trade Equilibrium
3. Global technological change
4. Local technological change
5. Extensions

Basic Environment

Basic Environment

- Consider a world economy with multiple countries $c \in \mathcal{C} \equiv \{1, ..., C\}$
- There is one factor of production, labor:
  - Labor is inelastically supplied and immobile across countries
  - L_c and w_c denote the endowment of labor and wage in country c
- There is one final good:
  - To produce the final good, a continuum of stages $s \in \mathcal{S} \equiv (0, S]$ must be performed (more on that on the next slide)
- All markets are perfectly competitive and all goods are freely traded
  - We use the final good as our numeraire

Basic Environment (Cont.)

- At each stage, producing 1 unit of intermediate good requires a fixed amount of previous intermediate good and a fixed amount of labor
  - "Intermediate good 0" is in infinite supply and has zero price
  - "Intermediate good S" corresponds to final good mentioned before
- Mistakes occur at a constant Poisson rate, $\lambda_c > 0$
  - λ_c measures total factor productivity (TFP) at each stage
  - Countries are ordered such that λ_c is strictly decreasing in c
- When a mistake occurs, intermediate good is entirely lost
- Formally, if a firm combines $q(s)$ units of intermediate good s with $q(s)ds$ units of labor, the output of intermediate good $s + ds$ is

$$q\left(s + ds\right) = \left(1 - \lambda_c ds\right) q\left(s\right)$$

▸ details

Free Trade Equilibrium

Definition

Definition 1 *A free trade equilibrium corresponds to output levels* $Q_c(\cdot) : S \longrightarrow \mathbb{R}^+$ *for all* $c \in C$, *wages* $w_c \in \mathbb{R}^+$ *for all* $c \in C$, *and intermediate good prices* $p(\cdot) : S \longrightarrow \mathbb{R}^+$, *such that:*

1. *firms maximize profit*

$$p(s + ds) \leq (1 + \lambda_c ds)\, p(s) + w_c ds$$

with equality if $Q_c(s') > 0$ *for all* $s' \in (s, s + ds]$

2. *good markets clear*

$$\sum_{c=1}^{C} Q_c(s_2) - \sum_{c=1}^{C} Q_c(s_1) = -\int_{s_1}^{s_2} \sum_{c=1}^{C} \lambda_c Q_c(s)\, ds$$

3. *labor markets clear*

$$\int_0^S Q_c(s)\, ds = L_c$$

Proposition

In any free trade equilibrium, there exists a sequence of stages $S_0 \equiv 0 < S_1 < ... < S_C = S$ *such that for all* $s \in \mathcal{S}$ *and* $c \in \mathcal{C}$, $Q_c(s) > 0$ *if and only if* $s \in (S_{c-1}, S_c]$.

- **Intuition 1 (hierarchy):**
  - Countries that are producing at later stages can leverage their productivity on larger amounts of inputs
  - Thus, efficiency requires countries to be more productive at the top
- **Intuition 2 (trade):**
  - Intermediate goods at later stages have lower labor cost shares
  - This makes them relatively cheaper to produce in high wage countries

Lemma

The pattern of vertical specialization and export levels satisfy

$$S_c = S_{c-1} - \left(\frac{1}{\lambda_c}\right) \ln\left(1 - \frac{\lambda_c L_c}{Q_{c-1}}\right), \text{ for all } c \in \mathcal{C}, \quad (1)$$

$$Q_c = e^{-\lambda_c (S_c - S_{c-1})} Q_{c-1}, \text{ for all } c \in \mathcal{C}, \quad (2)$$

with boundary conditions $S_0 = 0$ *and* $S_C = S$.

- **Notation:** $(S_1, ..., S_C) \equiv$ "pattern of vertical specialization"; $Q_c \equiv Q_c(S_c) \equiv$ "export level from country c"
- **Intuition (market clearing):**
  - (1): exogenous supply of labor in country c must be equal to the amount of labor demanded to perform all stages from S_{c-1} to S_c
  - (2): intermediate goods get lost at a constant rate when produced in c

Lemma

The world income distribution and export prices satisfy

$$w_{c+1} = w_c + (\lambda_c - \lambda_{c+1})\, p_c, \text{ for all } c < C, \quad (3)$$

$$p_c = e^{\lambda_c N_c} p_{c-1} + \left(e^{\lambda_c N_c} - 1\right)(w_c / \lambda_c), \text{ for all } c \in \mathcal{C}, \quad (4)$$

with boundary conditions $p_0 = 0$ *and* $p_C = 1$.

- **Notation:** $(w_1, ..., w_C) \equiv$ "world income distribution"; $p_c \equiv p(S_c) \equiv$ "price of exports from c"; and $N_c \equiv S_c - S_{c-1}$
- **Intuition (zero profit):**
  - (3): unit cost of production of S_c must be equal in c and $c+1$
  - (4): export price of c depends on import price + total labor cost

Proposition

There exists a unique free trade equilibrium. In this equilibrium, the pattern of vertical specialization and export levels are given by (1) *and* (2)*, and the world income distribution and export prices by* (3) *and* (4)*.*

- **Sketch of proof:**
  1. Use (1) and (2) to construct unique pattern of vertical specialization and vector of export levels (with Q_0 set to satisfy $S_C = S$)
  2. Use (3) and (4) to construct unique world income distribution and vector of export prices (with w_1 set to satisfy $p_C = 1$)

Summary

- Free trade equilibrium always exhibits vertical specialization
  - Compared to standard Ricardian models, *absolute* productivity differences are a source of comparative advantage between nations
- Note that according to our elementary theory of global supply chains:
  1. Poor countries have higher shares of primary production
  2. Rich countries tend to trade relatively more with rich countries
  3. Rich countries tend to import and export goods with higher prices

  $\Rightarrow$ *Supply-side* explanation of "Linder" stylized facts
- Our model also implies that after controlling for GDP, poor countries have higher ratio of value added to gross exports
  $\Rightarrow$ consistent with Johnson and Noguera (2010)

Comparative Statics

Definitions

- **Definition 2** *A country $c \in C$ is moving up (resp. down) the supply chain relative to the initial free trade equilibrium if $S'_c \geq S_c$ and $S'_{c-1} \geq S_{c-1}$ (resp. $S'_c \leq S_c$ and $S'_{c-1} \leq S_{c-1}$)*
- **Definition 3** *Inequality is increasing (resp. decreasing) among a given group $\{c_1, ...c_n\}$ of adjacent countries if $w'_{c+1}/w'_c \geq w_{c+1}/w_c$ (resp. $w'_{c+1}/w'_c \leq w_{c+1}/w_c$) for all $c_1 \leq c \leq c_n$*
- Definition 2 aims to speak to major concern in developed countries
  - "China is moving up the value chain"
- Definition 3 offers simple way to conceptualize changes in world income distribution in an economy with multiple countries.
  - Definition 3 is in terms of wages *per efficiency unit*

Global Technological Change

Increase in Complexity

Proposition

An increase in complexity (S) leads all countries to move up the supply chain and increases inequality between countries around the world.

- **Vertical specialization intuition:**
  - $S \uparrow$ decreases total output at all stages of production
  - Since labor supply must remain equal to demand, this must be accompanied by $N_c \uparrow$ in all countries

Increase in Complexity

Inequality intuition:

- From wage equation, relative wages satisfy

$$\frac{w_{c+1}}{w_c} = 1 + \frac{\lambda_c - \lambda_{c+1}}{(w_c / p_c)}, \text{ for all } c < C$$

Increase in Complexity

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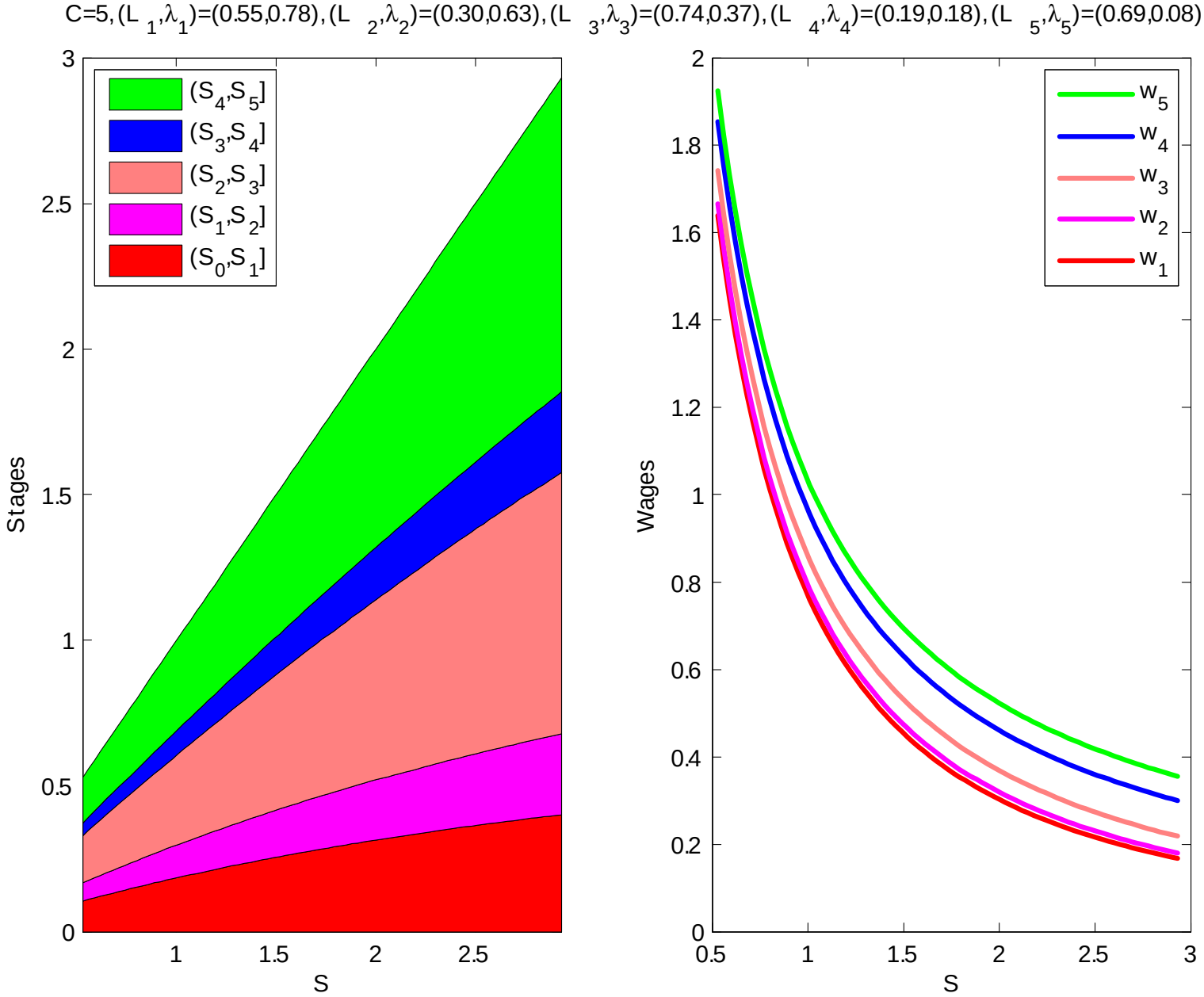
$$\frac{w_{c+1}}{w_c} = 1 + \frac{\lambda_c - \lambda_{c+1}}{(w_c / p_c)}, \text{ for all } c < C$$

  $\Rightarrow w_{c+1}/w_c$ decreasing in labor cost share, w_c/p_c, of c's export

- Countries are
  - Moving up into higher stages $\Rightarrow$ tends to raise p_{c-1}
  - Performing more stages
    - $\uparrow$ imports necessary to produce one unit of export, $e^{\lambda_c N_c}$
    - $\uparrow$ labor necessary to transform imports into exports, $\left(e^{\lambda_c N_c} - 1\right)/\lambda_c$
  - All effects tend to raise p_c, and in turn, to decrease labor cost share


C=5,(L 1,λ1)=(0.55,0.78),(L 2,λ2)=(0.30,0.63),(L 3,λ3)=(0.74,0.37),(L 4,λ4)=(0.19,0.18),(L 5,λ5)=(0.69,0.08)
(S4,S5]
(S3,S4]
(S2,S3]
(S1,S2]
(S0,S1]
Stages
S
w5
w4
w3
w2
w1
Wages
S

Complexity and World Income Distribution

- Mechanism is reminiscent of mechanism underlying terms-of-trade effects in standard Ricardian models
- Intuitively, $w_{c+1}/w_c \uparrow$ because c moves into sectors in which it has a comparative disadvantage (relative to $c+1$)
  - In our model, since c has a lower wage, these are the sectors with lower labor cost shares
  - In a standard Ricardian model, this would be the sectors in which c is relatively less productive
- There is, however, one important difference:
  - In our model, the pattern of comparative advantage depends on *endogenous* differences in labor cost shares across stages
  - In a standard Ricardian model, the same pattern only depends on *exogenous* productivity differences

Standardization

- **Standardization:** *uniform decrease in failure rates from* λ_c *to* $\lambda_c' \equiv \beta\lambda_c$ *for all* $c \in C$*, with* $\beta < 1$

Proposition

Standardization leads all countries to move up the supply chain and decreases inequality between countries around the world.

- **Intuition:**
  - Standardization raises output (and labor demand) at all stages
  - Must be offset by a reduction of output at earlier stages
    $\Rightarrow$ Poor countries reduce output at each stage, pushing all countries up

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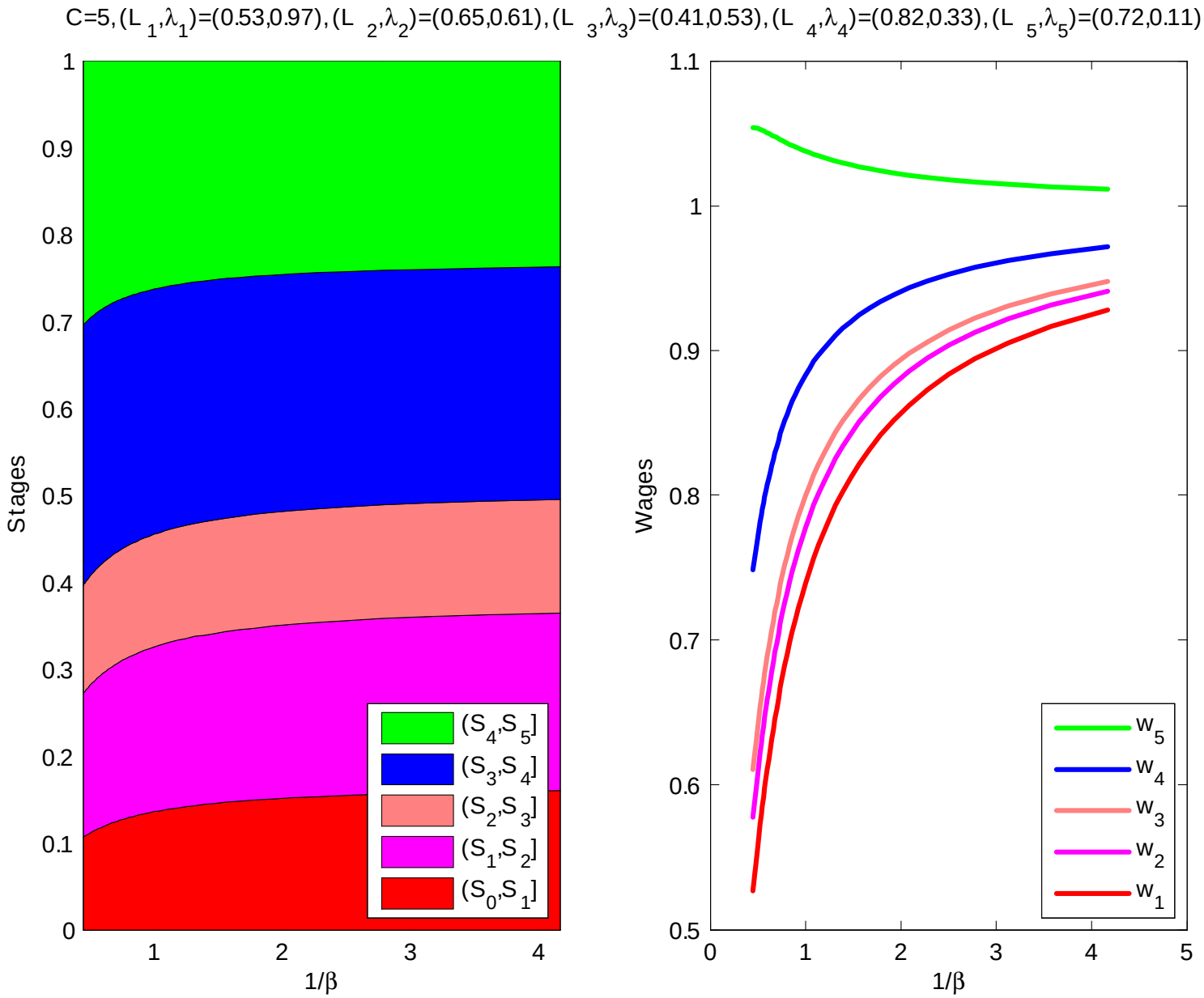
    $\Rightarrow$ Poor countries reduce output at each stage, pushing all countries up
  - Direct effect of standardization on relative wages is to decrease inequality (if $\beta = 0$, having lower failure rate λ_c provides no benefit)
    $\Rightarrow$ Direct effect necessarily dominates


C=5,(L 1,λ1)=(0.53,0.97),(L 2,λ2)=(0.65,0.61),(L 3,λ3)=(0.41,0.53),(L 4,λ4)=(0.82,0.33),(L 5,λ5)=(0.72,0.11)
Stages
1/β
(S4,S5]
(S3,S4]
(S2,S3]
(S1,S2]
(S0,S1]
Wages
1/β
w5
w4
w3
w2
w1

Standardization, Product Cycles, and Immiserizing Growth

- Standardization leads to **product cycles**:
  - Standardization induces poor countries to perform more stages
  - Results reminiscent of Vernon's (1966) "product cycle hypothesis"
  - As this happens, inequality between nations decreases around the world
- Standardization may lead to **immiserizing growth**:
  - Welfare may fall in the most technologically advanced countries because of a deterioration of their terms-of-trade
  - Compared to Bhagwati (1958):
    1. Standardization proportionately lowers failure rates in *all* countries
    2. Standardization proportionately lowers failure rates at *all* stages

Local Technological Change

Labor endowment growth: *Increase in labor endowment* L_{c_0}

Proposition

Labor-endowment growth in c_0 *leads all countries* $c < c_0$ *to move down the supply chain and all countries* $c > c_0$ *to move up.*

- **Intuition:**
  1. $\nearrow$ in labor supply in c_0 $\nearrow$ total output at all stages
  2. Since labor supply $=$ labor demand, $N_c \searrow$ for all $c \neq c_0$
  3. By iteration, this decrease in N_c can only occur if all countries below c_0 move down and all countries above c_0 move up
  4. Since the total measure of stages is constant, $N_{c_0} \nearrow$

Proposition

Labor-endowment growth in c_0 *decreases inequality among countries* $c \in \{1, ..., c_0\}$*, increases inequality among countries* $c \in \{c_0, ..., c_1\}$*, and decreases inequality among countries* $c \in \{c_1, ..., C\}$*, with* $c_1 \in \{c_0 + 1, ..., C\}$.

- **Intuition (bottom of the chain):**
  1. At the bottom of the chain countries (i) move down into lower stages and (ii) perform fewer stages
  2. Both effects $\searrow$ the price of goods traded in that region of the chain, and in turn, $\nearrow$ their labor cost share
  3. Thus, $w_{c+1}/w_c \searrow$ as the labor cost share, w_c/p_c, of c's exports $\nearrow$

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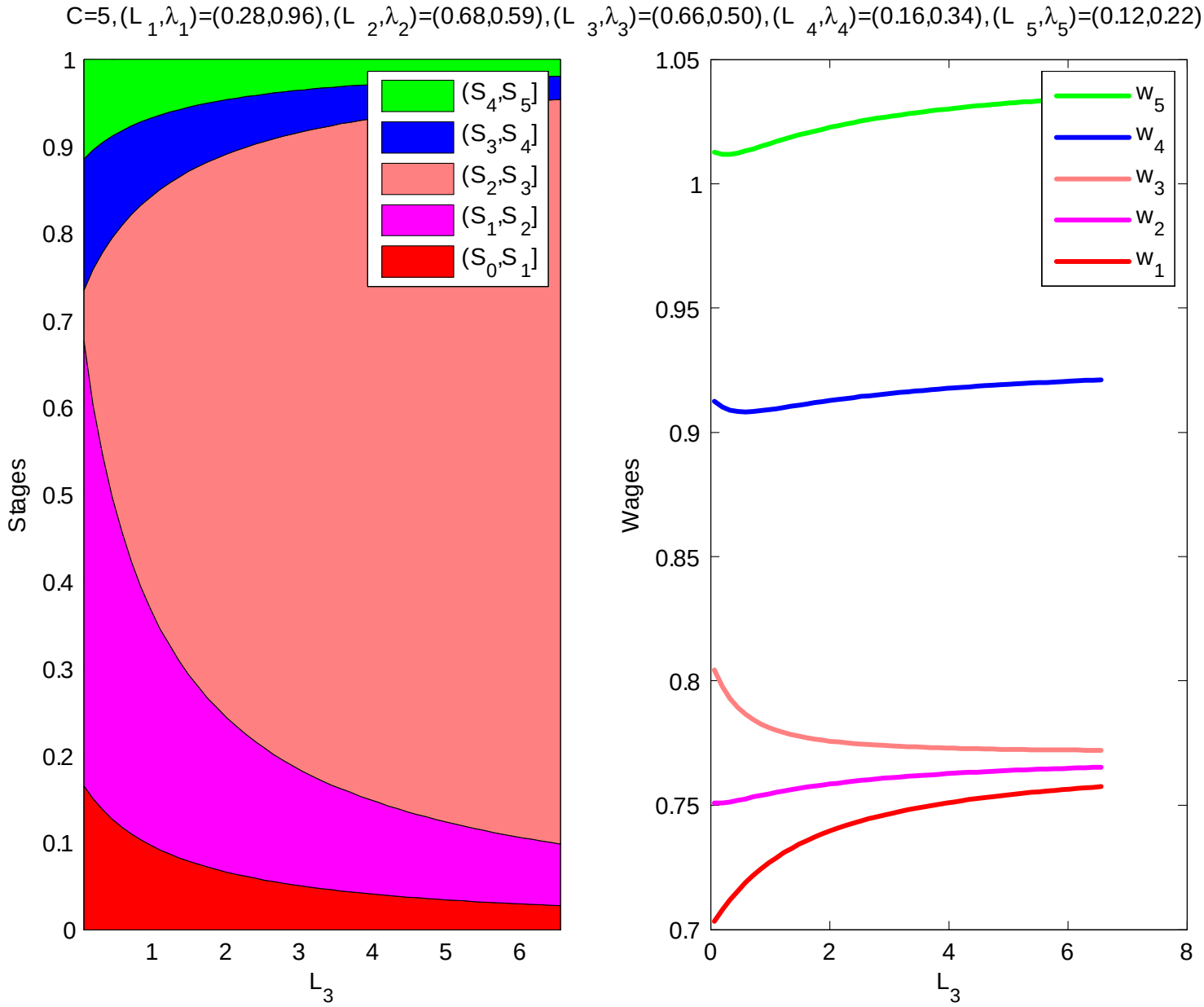
  3. Thus, w_{c+1}/w_c $\searrow$ as the labor cost share, w_c/p_c, of c's exports $\nearrow$
- **Intuition (top of the chain):**
  - *Endogenous* differences in labor cost shares $\Rightarrow$ non-monotonic effects


C=5,(L 1,λ1)=(0.28,0.96),(L 2,λ2)=(0.68,0.59),(L 3,λ3)=(0.66,0.50),(L 4,λ4)=(0.16,0.34),(L 5,λ5)=(0.12,0.22)
Stages
L3
(S4,S5]
(S3,S4]
(S2,S3]
(S1,S2]
(S0,S1]
Wages
L3
w5
w4
w3
w2
w1

Comparison with "Simultaneous" Ricardian models

- Consider Ricardian model w/ ladder of countries (e.g. Krugman 1986)
- If richest countries move up, inequality increases
  - Relative wage = relative productivity in "cutoff" sector
  - Richer countries are relatively more productive in sectors higher up (otherwise they would not be specializing in these sectors!)
- Here as richest countries move up, inequality may decrease
  - Later stages have lower labor cost shares *in a given equilibrium*
  - But endogeneity $\Rightarrow$ labor cost share of later stages *in new equilibrium* may be higher than of earlier stages *in initial equilibrium*

Routinization

Pattern of vertical specialization

Routinization: *Decrease in failure rate* λ_{c_0}

Proposition

Routinization in c_0 *increases the measure of stages performed in all countries* $c < c_0$ *and decreases the measure of stages performed in all countries* $c > c_0$*. In turn, all countries* $c \neq c_0$ *move up the supply chain.*

- Through fragmentation of the production process across borders, routinization in one country leads *all* its trading partners to move up (even in the absence of TFP growth in any of these countries)
- Labor-augmenting technical progress and routinization have the exact same effects at the top, but *opposite* effects at the bottom

Routinization

Pattern of vertical specialization

- **Basic idea:**
  Labor markets must clear both before and after a given TFP shock
- **Intuition (top of the chain):**
  1. $\searrow$ in failure rate in c_0 $\nearrow$ total output at all stages
  2. Since labor supply $=$ labor demand, N_c $\searrow$ for all $c \neq c_0$ etc.
- **Intuition (bottom of the chain):**
  1. $\searrow$ in failure rate in c_0 $\nearrow$ total labor demand of countries $c \geq c_0$
  2. Thus, countries at the bottom must $\nearrow$ number of stages they perform and move up to offset excess labor demand at the top

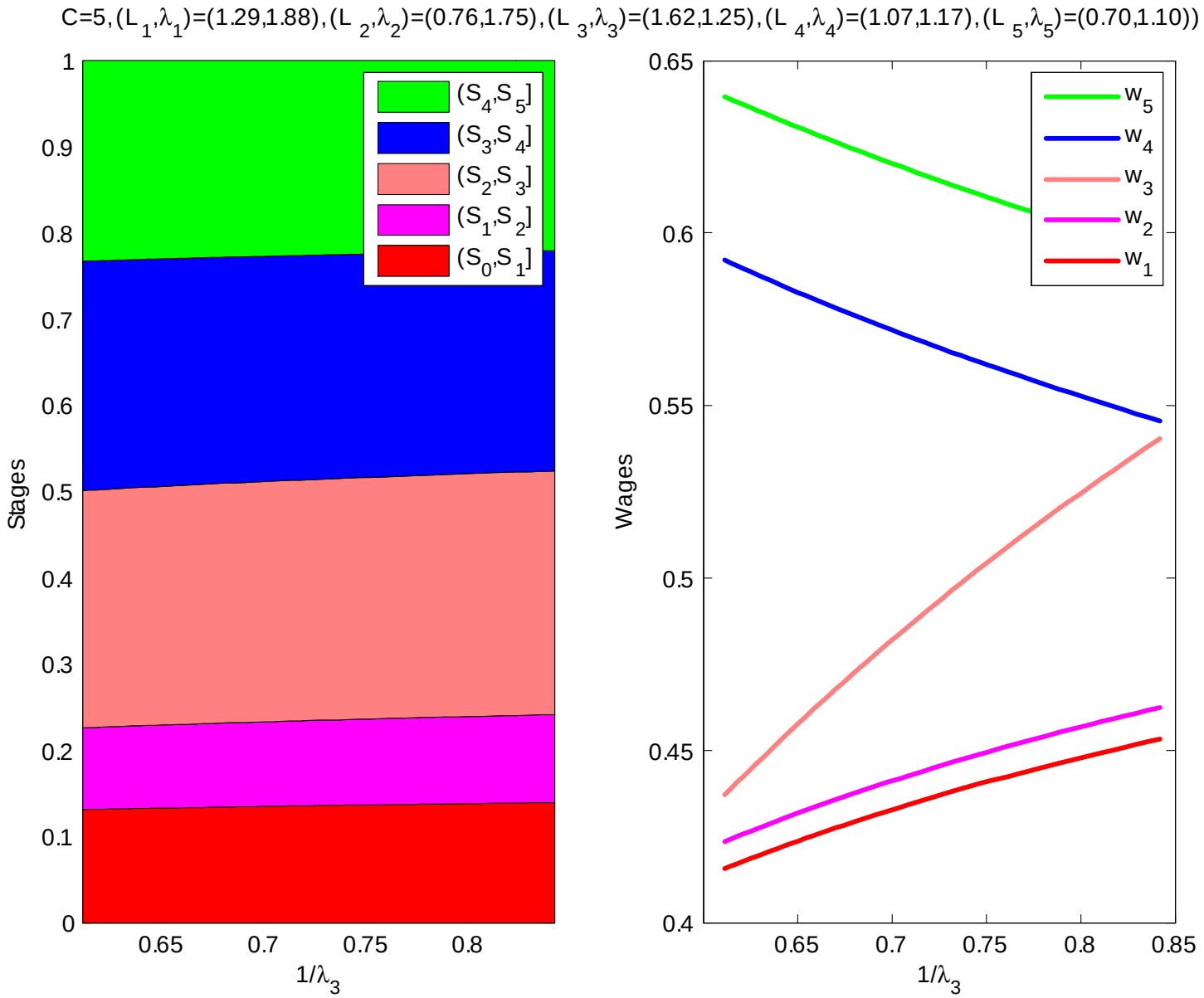
Routinization

World income distribution

Proposition

Routinization in c_0 increases inequality among countries $c \in \{1, ..., c_0 - 1\}$, decreases inequality among countries $c \in \{c_0, c_0 + 1\}$, increases inequality among countries $c \in \{c_0 + 1, ..., c_1\}$, and decreases inequality among countries $c \in \{c_1, ..., C\}$, with $c_1 \in \{c_0 + 1, ..., C\}$.

- As before, changes in the pattern of vertical specialization naturally translate into changes in inequality between nations
- At the bottom, routinization increases inequality between nations
- Though poor countries are moving up, they are relatively worse off
  - Since technological change comes from abroad, they still have a comparative disadvantage in later stages of production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(S3,S4]
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(S1,S2]
(S0,S1]
Wages
w5
w4
w3
w2
w1

Extensions

Coordination Costs

Assumptions

- Likelihood of a defect in final good is increasing in number of times the intermediate goods used in its production have crossed a border
- If production of one unit of final good involves n international transactions, final good is defect free with probability $(1-\tau)^n$
- Final good is freely traded and use it as our numeraire
- All international transactions are perfectly observable by all firms
  - Two units of intermediate good s may command two different prices if their production requires different number of international transactions
  - Competitive equilibria remain Pareto optimal

Coordination Costs

Cross-sectional predictions

- Let $c^u(s)$ denote the country in which stage s has been performed for the production of a given unit u.

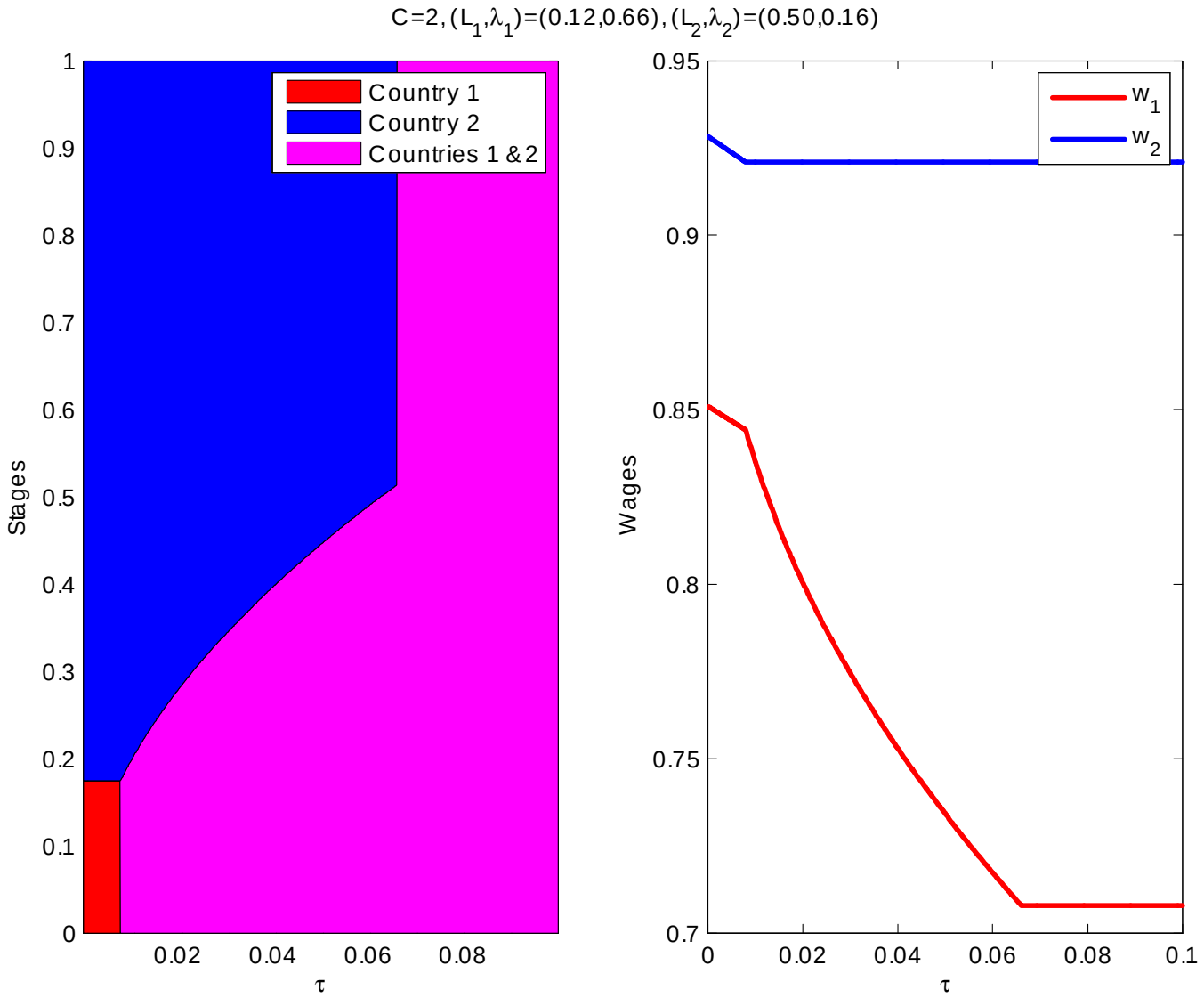
Proposition (Coordination Costs)

In any competitive equilibrium, the allocation of stages to countries, $c^u : S \to C$, is increasing in s for all $u \in [0, \sum_{c \in C} Q_c(S)]$.

- For any unit u, production still involves vertical specialization, but $c^u(\cdot)$ may now vary across units
- Using previous lemma, we can characterize competitive equilibria:
  1. guess structure of equilibrium (e.g. some units produced entirely in country 1, whereas all other units produced jointly in all countries)
  2. verify ex post that guess is correct

Coordination Costs

Overshooting



Simultaneous Production and Assembly

- Multiple supply chains, indexed by $n \in \mathcal{N} \equiv \{1, ..., N\}$, each associated with a part
  - Failure rates are constant across chains
  - But supply chains may differ in terms of their complexity, S^n
- Parts are assembled into a unique final good using labor

$$Y_c = F\left(X_c^1, ..., X_c^N, A_c\right)$$

Proposition (Simultaneous Production)

In any free trade equilibrium, there exists a sequence of stages $S_0 \equiv 0 \leq S_1 \leq ... \leq S_C = S^N$ *such that for all* $n \in N$, $s \in (0, S^n]$, *and* $c \in C$, $Q_c^n(s) > 0$ *if and only if* $s \in (S_{c-1}, S_c]$. *Furthermore, if country* c *is engaged in parts production,* $A_c < L_c$, *then all countries* $c' > c$ *are only involved in parts production,* $A_{c'} = 0$.

Simultaneous Production and Assembly

Cross-sectional predictions

- Three restrictions on the pattern of international specialization:
  1. The poorest countries tend to specialize in assembly, while the richest countries tend to specialize in parts production
  2. Amongst the countries that produce parts, richer countries produce and export at later stages of production
  3. Whereas middle-income countries tend to produce all parts, the richest countries tend to specialize in only the most complex ones
- Compared to benchmark model:
  - Trade is more likely to be concentrated among countries with similar levels of GDP per capita if exports and imports occur along supply chains rather than between "part producers" and "assemblers", i.e. in industries in which production process consists of very complex parts

Imperfect Observability of Mistakes

- Mistakes are imperfectly observed with probability $\beta_c \in [0,1]$
- Quality, θ, is the probability that an intermediate is defect free
- If a firm from country c combines $q[s,\theta(s)]$ units of good s with quality $\theta(s)$ with $q[s,\theta(s)]\,ds$ units of labor, output at $s+ds$ is

$$q[s+ds,\theta(s+ds)] = (1-\beta_c\lambda_c ds)\,q[s,\theta(s)].$$

- Using Bayes' rule, quality at stage $s+ds$ is

$$\theta(s+ds) = [1-(1-\beta_c)\lambda_c ds]\,\theta(s).$$

Proposition (Imperfect Observability of Mistakes)

Suppose that $\beta_c\lambda_c$ is strictly decreasing in c and λ_c is weakly decreasing in c. Then in any symmetric free trade equilibrium, there exists a sequence of stages $S_0 \equiv 0 < S_1 < ... < S_C = S$ such that for all $s \in S$ and $c \in C$, $Q_c(s) > 0$ if and only if $s \in (S_{c-1}, S_c]$.

Imperfect Observability of Mistakes

- Countries with higher failures rates and better quality controls specialize in earlier stages
- Suppose an unobserved mistake ocurrs at stage s'
  - firms add labor to this defective unit as it moves up the chain
  - more labor gets wasted the lower is s'

  $\Rightarrow$ It is efficient to have countries with better quality control, all else equal, at the bottom of the chain
- Implication:
  - Richer countries likely to have both $\downarrow$ failure rates and $\uparrow$ quality control
  - Relative importance of these two considerations in different industries may determine who operates at the top of global supply chains

General Production Functions

- Consider following CES production process

$$q(s+\delta s) = e^{-\lambda_c(s)\delta s}\left\{(1-\delta s)q(s)^{\frac{\sigma-1}{\sigma}} + \delta s\left[I(s)/\delta s\right]^{\frac{\sigma-1}{\sigma}}\right\}^{\frac{\sigma}{\sigma-1}}$$

- Production process in paper corresponds to limit as $\delta s \longrightarrow 0$ if
  1. Leontief: $\sigma = 0$
  2. Stages only differ in the order they are performed: $\lambda_c(s) \equiv \lambda_c$
  3. Production subject to mistakes: $\lambda_c > 0$

General Production Functions

- Consider following CES production process

$$q(s+\delta s) = e^{-\lambda_c(s)\delta s}\left\{(1-\delta s)q(s)^{\frac{\sigma-1}{\sigma}} + \delta s\left[I(s)/\delta s\right]^{\frac{\sigma-1}{\sigma}}\right\}^{\frac{\sigma}{\sigma-1}}$$

- Production process in paper corresponds to limit as $\delta s \longrightarrow 0$ if
  1. Leontief: $\sigma = 0$
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Proposition (General Production Function)

Suppose that $\sigma < 1$ and that $\lambda_c(s)$ is strictly decreasing in c, differentiable in s with either $\lambda_c'(s) > 0$ or $\lambda_c'(s) = 0$ for all s, and weakly submodular in (s, c). Then in any free trade equilibrium, there exists a sequence of stages $S_0 \equiv 0 < S_1 < ... < S_C = S$ such that for all $s \in S$ and $c \in C$, $Q_c(s) > 0$ if and only if $s \in (S_{c-1}, S_c]$.

General Production Functions

- Previously, result held b/c w_c / p_c falls along chain, making goods at top of chain relatively cheaper to produce in high w_c countries
- Result holds now under three conditions:
  1. $\lambda_c(s)$ increasing in $s \Rightarrow p_c$ rising along chain
  2. $\sigma < 1 \Rightarrow w_c / p_c$ falling along chain
     $\Rightarrow$ absent comparative advantage across stages, high w_c countries specialize in later stages
  3. $\lambda_c(s)$ weakly submodular in $(s, c) \Rightarrow$ comparative advantage reinforces pattern of international specialization

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  3. $\lambda_c(s)$ weakly submodular in $(s, c) \Rightarrow$ comparative advantage reinforces pattern of international specialization
- Forces shaping inequality same as before, but comparative statics more involved
  - As an example, consider extending to allow only $\lambda_c < 0$
    - All comparative static results on specialization still hold
    - However, changes in N_c no longer sufficient to predict changes in inequality ▸ details

Concluding Remarks

Summary

- We have developed an elementary theory of global supply chains
  - Because of the sequential nature of production, absolute productivity differences are a source of comparative advantage among nations.
- Using this theory, we have taken a first step towards analyzing how vertical specialization shapes the interdependence of nations
- Among other things, we have shown that:
  - Standardization can cause welfare loss in rich countries
  - Local technological progress tends to spill over very differently at bottom and top of the chain

Other Applications

- While we have emphasized the consequences of vertical specialization for the interdependence of nations, we believe that our general results also have useful applications outside of international trade
  - Sequential production processes are pervasive in practice
  - They may involve workers of different skills (labor)
  - They may also involve firms of different productivity (IO)
- Whatever the particular context may be, our theory may help shed a new light on how vertical specialization shapes the interdependence between different actors of a given supply chain.

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Increase in Complexity

Inequality intuition:

- From price equation, relative wages satisfy

$$\frac{w_{c+1}}{w_c} = 1 + \frac{\lambda_c - \lambda_{c+1}}{(w_c / p_c)}, \text{ for all } c < C$$

  $\Rightarrow w_{c+1}/w_c$ decreasing in labor cost share, w_c/p_c, of c's export

- Countries are
  - Moving up into higher stages $\Rightarrow$ tends to raise p_{c-1}
  - Performing more stages
    - $\uparrow$ imports necessary to produce one unit of export, $e^{\lambda_c N_c}$
    - $\uparrow$ labor necessary to transform imports into exports, $\left(e^{\lambda_c N_c} - 1\right)/\lambda_c$
  - All effects tend to raise p_c, and in turn, to decrease labor cost share

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