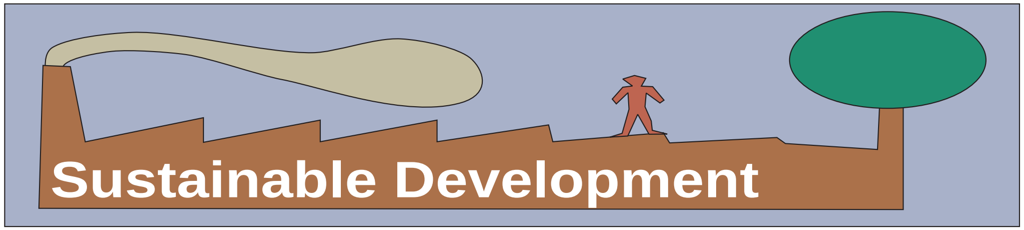

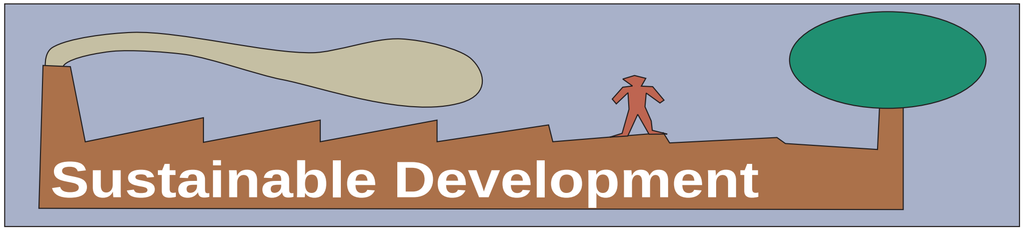

Core lecture 3

Natural resource demand and Solow’s mechanisms

The mechanisms revisited

The mechanisms revisited

1. Use less of the resource (increase resource efficiency) in production of one or more product categories;
2. Shift to an alternative (substitute) resource in production of one or more product categories.
3. Substitute on the consumption side away from product categories in which the production process is resource-intensive.

The mechanisms revisited

Solow (1973) argues that higher resource prices should drive each mechanism directly.

But he also argues that if resource prices drive up the *factor share* of the resource, that should incentivise research on both efficiency and alternatives.

Hart (2013) shows that Solow (1973) was correct: under reasonable assumptions, investment in improved productivity of an input is in proportion to the factor share of that input.

What are the implications of this for (a) explaining past data, (b) predicting the future, and (c) policy?

We start by looking at resource efficiency, then turn to substitute resources.

The mechanisms revisited

Finally we turn to changing consumption patterns, linking the discussion to *Jevons' paradox* and the *rebound effect*, showing the importance of *substitution* and *income* effects.

We also introduce the idea of social norms, allowing one agent's utility to be affected by what they see others doing. How does this affect the analysis?

Resource efficiency and DTC

Resource efficiency in the production function

Resource efficiency in the production function

$$Y = F(A_L L, A_R R).$$

$$Y = (A_L L)^{\alpha}(A_R R)^{1-\alpha} = A L^{\alpha} R^{1-\alpha}.$$

$$Y = \min\{A_L L, A_R R\}.$$

$$Y = [\gamma(A_L L)^{\epsilon} + (1-\gamma)(A_R R)^{\epsilon}]^{1/\epsilon}.$$

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Why not Cobb–Douglas?

Resource efficiency in the production function

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$$Y = (A_L L)^{\alpha}(A_R R)^{1-\alpha} = A L^{\alpha} R^{1-\alpha}.$$

$$Y = \min\{A_L L, A_R R\}.$$

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Advantage of Leontief? Think of making hammers from steel.

Resource efficiency in the production function

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$$Y = \min\{A_L L, A_R R\}.$$

$$Y = [\gamma (A_L L)^{\epsilon} + (1-\gamma)(A_R R)^{\epsilon}]^{1/\epsilon}.$$

What values are possible for ϵ?

Discuss special cases.

Advantages of CES?

Resource efficiency in the production function

Assume an economy with 10 people on an island, and 10 trees/week wash up on the beach. Furthermore, the islanders have a technology called 'knives' which allows them to cut the trees into planks, which can rapidly be made into houses (final product). They manage to make 0.01 houses per week.

What do they need more of to boost their rate of housebuilding? Suggest values for the elasticity of substitution between the inputs, and knowledge levels. Explain briefly.

Resource efficiency in the production function

Now assume that the islanders invent a technology called 'sawmills' (and are somehow able to obtain the necessary capital goods). What do they need more of now in order to boost their rate of housebuilding? Suggest new values for the knowledge levels. Explain briefly.

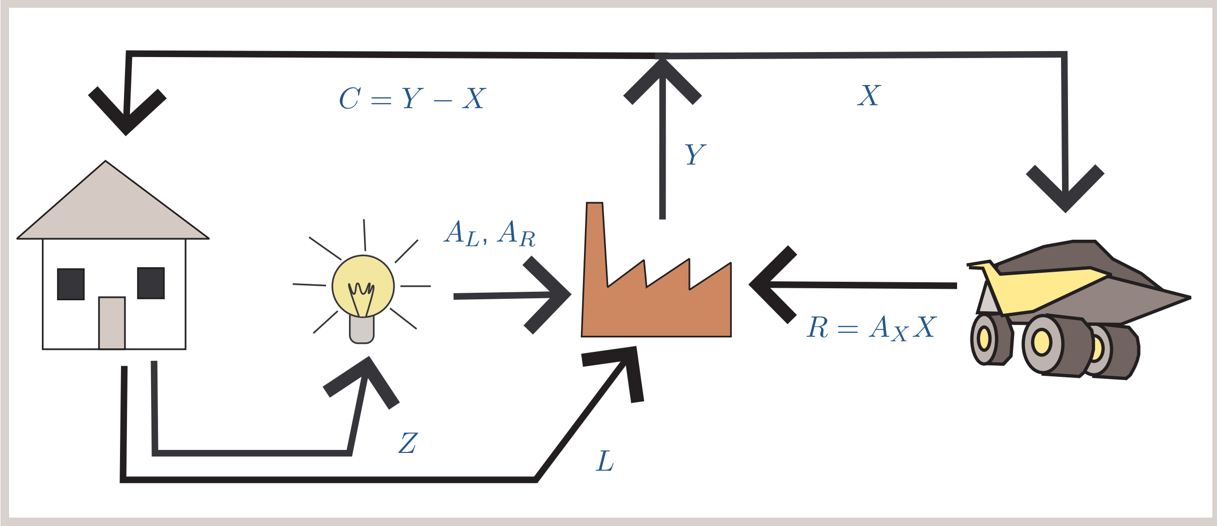
An aggregate DTC model

Ideally we would build our aggregate model from micro-foundations of individual firms investing in resource efficiency to save on their input costs, and these firm-level knowledge stocks then combining to form a general stock of knowledge about resource efficiency.

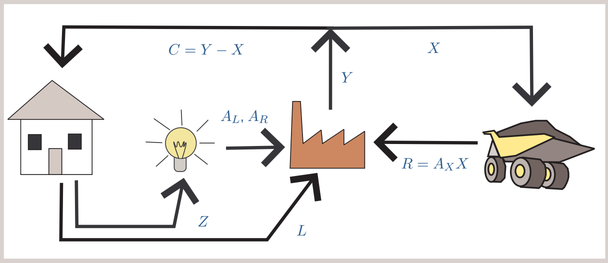
How this can be done is outlined in Hart (2013). We skip this step and go straight to the aggregate level, and take the result from Hart (2013) that aggregate investment in resource efficiency is in proportion to the aggregate factor share of the resource.

$$\frac{Z_R}{Z_L} = \frac{w_R R}{w_L L}.$$

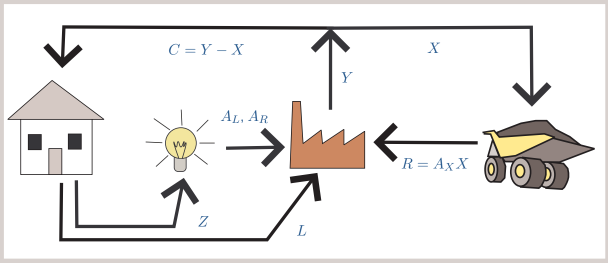
An aggregate DTC model



An aggregate DTC model



An aggregate DTC model



Given the production function

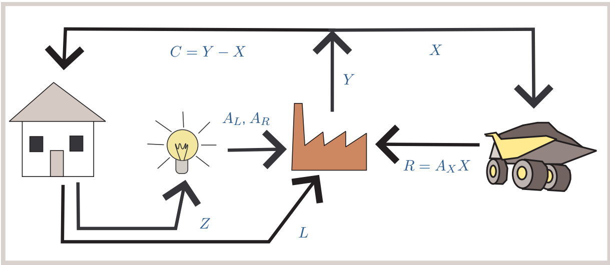
$$Y = [(A_L L)^\epsilon + (A_R R)^\epsilon]^{1/\epsilon}$$

first-order conditions yield

$$\frac{Z_R}{Z_L} = \frac{w_R R}{w_L L} = \left(\frac{A_R R}{A_L L}\right)^\epsilon = \left(\frac{A_R/w_R}{A_L/w_L}\right)^{\epsilon/(1-\epsilon)}.$$

Since ϵ is negative, if w_R increases (exogenously) relative to w_L, the resource share increases and Z_R increases relative to Z_L.

An aggregate DTC model



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But what is the (long-run) effect on A_R/A_L?

The knowledge production function

The knowledge production function

The long-run effect on A_R/A_L depends on the knowledge production function (also known as the *innovation possibilities frontier*).

The knowledge production function

The long-run effect on A_R/A_L depends on the knowledge production function (also known as the *innovation possibilities frontier*).

A popular assumption in the literature (see for instance Smulders and de Nooij, 2003, and Acemoglu et al, 2012) is that knowledge stocks in different sectors grow *independently* of each other. For instance

$$A_{Lt} = A_{Lt-1} + (A_{Lt-1}/\zeta_L)Z_{Lt}^{\phi}$$

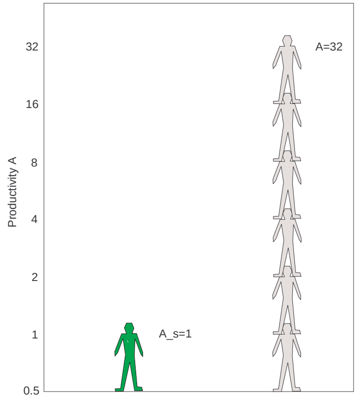
and

$$A_{Rt} = A_{Rt-1} + (A_{Rt-1}/\zeta_R)Z_{Rt}^{\phi}.$$

So new knowledge builds entirely on existing knowledge within the same sector.

The knowledge production function

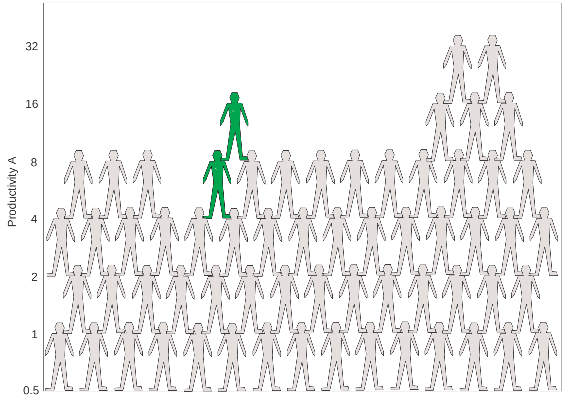
Using Isaac Newton's metaphor or researchers standing on each other's shoulders, we can picture independent knowledge stocks as follows.



So historical within-sector research is critical to the current level of productivity in a sector: a delay of 50 years in starting research in a sector will put that sector 50 years behind, forever. Linked to this, early researchers in a sector are indispensable for later advances; the value of within-sector spillovers is thus very large.

The knowledge production function

A lot of empirical work—perhaps starting with Trajtenberg et al (1992)—shows that sector-specific research builds on prior research both within the sector and outside. This case is illustrated (schematically) below.



How can we capture this idea in a tractable mathematical formulation which can be calibrated econometrically, and then used in theoretical models?

The knowledge production function

$$A_{Lt} - A_{Lt-1} = F(A_{Lt-1}, A_{Rt-1}) Z_{Lt}^{\phi} / \zeta_L$$

and $$A_{Rt} - A_{Rt-1} = F(A_{Rt-1}, A_{Lt-1}) Z_{Rt}^{\phi} / \zeta_R.$$

A possible formulation for F would be CES, so for instance

$$F(A_{Rt-1}, A_{Lt-1}) = (A_{Rt-1}^{\epsilon} + \sigma A_{Lt-1}^{\epsilon})^{1/\epsilon}.$$

Here ϵ is between 0 and 1, and σ is a measure of the weight of each unit of labour–capital-augmenting knowledge in helping to boost resource-augmenting knowledge. See Hart (2019) for a simpler alternative where $\epsilon = 1$.

Independent knowledge stocks

Independent knowledge stocks

Recall that with independent knowledge stocks we have

$$A_{Lt} = A_{Lt-1} + (A_{Lt-1}/\zeta_L) Z_{Lt}^{\phi}$$

and

$$A_{Rt} = A_{Rt-1} + (A_{Rt-1}/\zeta_R) Z_{Rt}^{\phi}.$$

so

$$\frac{A_{Lt} - A_{Lt-1}}{A_{Rt} - A_{Rt-1}} = \frac{A_{Lt-1}}{A_{Rt-1}} \frac{\zeta_R}{\zeta_L} \left(\frac{Z_{Lt}}{Z_{Rt}} \right)^{\phi}. \quad (1)$$

Independent knowledge stocks

$$\frac{A_{Lt} - A_{Lt-1}}{A_{Rt} - A_{Rt-1}} = \frac{A_{Lt-1}}{A_{Rt-1}} \frac{\zeta_R}{\zeta_L} \left(\frac{Z_{Lt}}{Z_{Rt}} \right)^{\phi} . \qquad (1)$$

Independent knowledge stocks

$$\frac{A_{Lt} - A_{Lt-1}}{A_{Rt} - A_{Rt-1}} = \frac{A_{Lt-1}}{A_{Rt-1}} \frac{\zeta_R}{\zeta_L} \left(\frac{Z_{Lt}}{Z_{Rt}} \right)^{\phi} . \qquad (1)$$

For balanced growth we require that A_L and A_R both grow at constant rates, which implies that $(A_{Lt}/A_{Lt-1})/(A_{Rt}/A_{Rt-1})$ is constant. But eqn (1) tells us that there is a unique Z_L/Z_R for which this holds, and hence a unique level for the relative factor shares in balanced growth.

Furthermore, this b.g.p. is stable. Imagine we are on it, and w_R/w_L increases. Then Z_R/Z_L increases, A_R/A_L increases, and the factor share of R goes down again, ending up at the original level.

Independent knowledge stocks

On a b.g.p.,

$$\frac{A_L L}{A_R R}$$

is constant. Therefore the factor shares are constant. The long-run aggregate production function 'appears to be' Cobb–Douglas!

$$Y = AL^{1-\alpha} R^{\alpha}.$$

The aggregate data also matches Cobb–Douglas!!

Problems with independent knowledge stocks

Problems with independent knowledge stocks

The model predicts that if w_R is constant while w_L increases—which is what we see in the data—then A_R/A_L should decline.

We do not observe such a decline. In fact A_R seems to grow at least as fast as A_L, at least in the case of energy where there is clear evidence.

See for instance Fouquet and Pearson (2006) on light production in the U.K. over seven centuries. While A_L grew by a factor of around 15, A_R for this sector grew by a factor of 1000.

Consider also increases in the efficiency of the generation of motive power from primary energy, from Newcomen through Watt to modern power stations.

Problems with independent knowledge stocks

The model of linked knowledge growth makes far more sense. Now, because general knowledge A_L is used to boost resource-specific knowledge A_R, increases in A_L also tend to drive A_R up (think of a rising tide of knowledge raising all the boats), even if w_R is falling relative to w_L.

If we put such links in the model then A_R grows even when w_R is constant, but the model no longer matches the quantity data since R/Y declines.

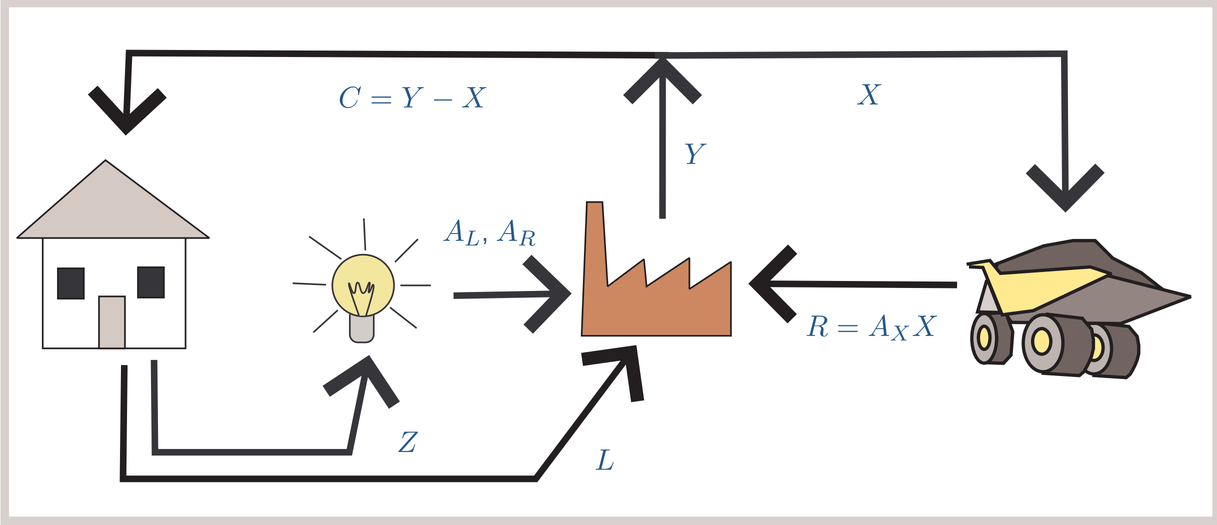
The obvious reason for the increase in R is not a lack of technological progress, but a shift into resource-intensive goods and production methods. We return to this in the next Core lecture.

Alternative resource inputs and DTC

Building a model

Building a model

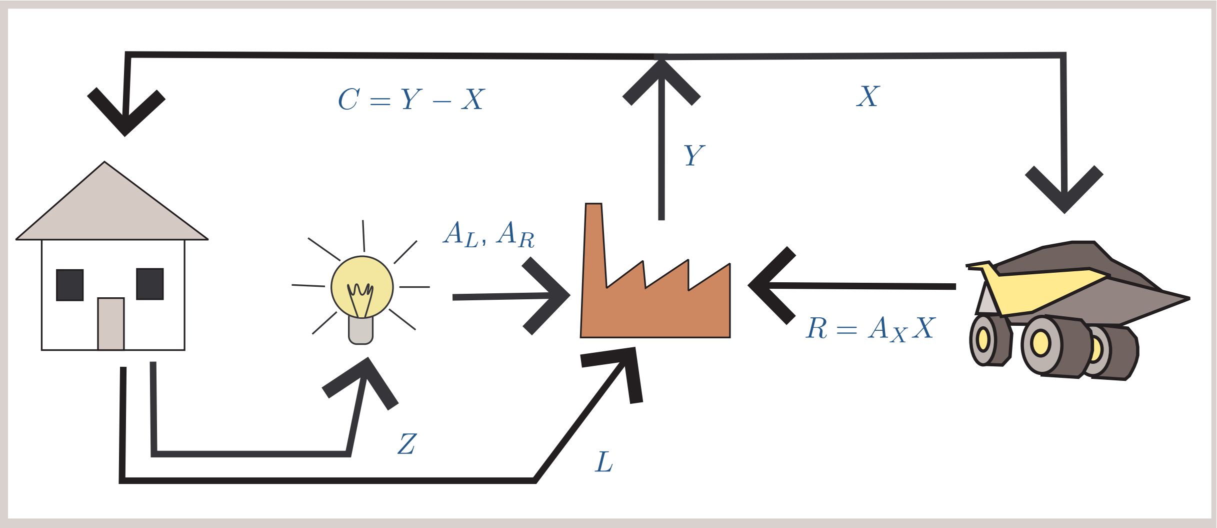
Recall the structure and production function for the resource-efficiency model.



$$Y = [(A_L L)^\epsilon + (A_R R)^\epsilon]^{1/\epsilon}.$$

Building a model

Now we focus on R, and simplify the final-good production function by going back to Cobb–Douglas.



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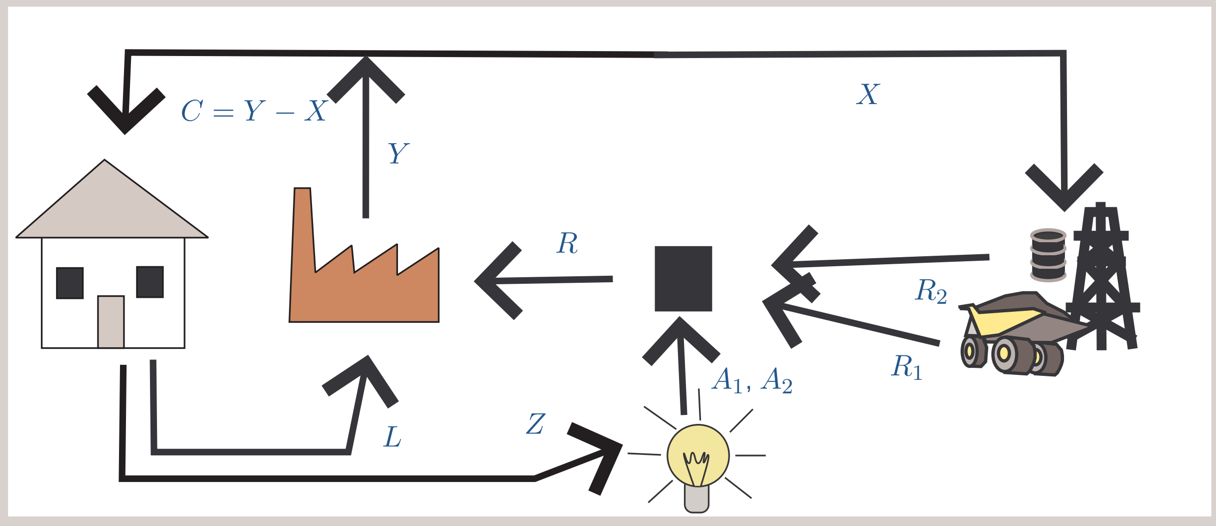

$$Y = (A_L L)^\alpha R^{1-\alpha};$$

$$R = [(A_1 R_1)^\epsilon + (A_2 R_2)^\epsilon]^{1/\epsilon}.$$

Building a model

$$Y = (A_L L)^{\alpha} R^{1-\alpha};$$

$$R = [(A_1 R_1)^{\epsilon} + (A_2 R_2)^{\epsilon}]^{1/\epsilon}.$$

Building a model

$$Y = (A_L L)^\alpha R^{1-\alpha};$$
$$R = [(A_1 R_1)^\epsilon + (A_2 R_2)^\epsilon]^{1/\epsilon}.$$

What can we say about ϵ?

Building a model

$$Y = (A_L L)^{\alpha} R^{1-\alpha};$$
$$R = [(A_1 R_1)^{\epsilon} + (A_2 R_2)^{\epsilon}]^{1/\epsilon}.$$

What can we say about ϵ?

$$\frac{Z_1}{Z_2} = \frac{w_1 R_1}{w_2 R_2} = \left(\frac{A_1 R_1}{A_2 R_2}\right)^{\epsilon} = \left(\frac{A_1/w_1}{A_2/w_2}\right)^{\epsilon/(1-\epsilon)}.$$

Since $\epsilon > 0$, if w_1 increases (exogenously) relative to w_2, the share of R_1 decreases and Z_1 decreases relative to Z_2.

Building a model

$$Y = (A_L L)^\alpha R^{1-\alpha};$$
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Since $\epsilon > 0$, if w_1 increases (exogenously) relative to w_2, the share of R_1 decreases and Z_1 decreases relative to Z_2.

Again, how we model the knowledge production function is crucial.

Independent knowledge stocks

Independent knowledge stocks

$$\frac{A_{Lt} - A_{Lt-1}}{A_{Rt} - A_{Rt-1}} = \frac{A_{Lt-1}}{A_{Rt-1}} \frac{\zeta_R}{\zeta_L} \left(\frac{Z_{Lt}}{Z_{Rt}} \right)^{\phi} . \quad (1)$$

Independent knowledge stocks

$$\frac{A_{1t} - A_{1t-1}}{A_{2t} - A_{2t-1}} = \frac{A_{1t-1}}{A_{2t-1}} \frac{\zeta_2}{\zeta_1} \left(\frac{Z_{1t}}{Z_{2t}} \right)^{\phi} . \qquad (2)$$

Independent knowledge stocks

$$\frac{A_{1t} - A_{1t-1}}{A_{2t} - A_{2t-1}} = \frac{A_{1t-1}}{A_{2t-1}} \frac{\zeta_2}{\zeta_1} \left(\frac{Z_{1t}}{Z_{2t}} \right)^{\phi} . \quad (2)$$

For balanced growth we now require that A_1 and A_2 both grow at constant rates, which implies that $(A_{1t}/A_{1t-1})/(A_{2t}/A_{2t-1})$ is constant. As before, eqn (2) tells us that there is a unique Z_1/Z_2 for which this holds, and hence a unique level for the relative factor shares in balanced growth.

However, this b.g.p. is not stable. Imagine we are on it, and w_1/w_2 increases. Then the factor share of R_1 decreases, Z_1/Z_2 decreases, A_1/A_2 decreases, and the factor share of R_1 goes down even more.

The only stable points are corners where we only use one of the inputs and not the other!

Independent knowledge stocks

Lock-in! Big policy implications if we are in the 'wrong' corner.

Independent knowledge stocks

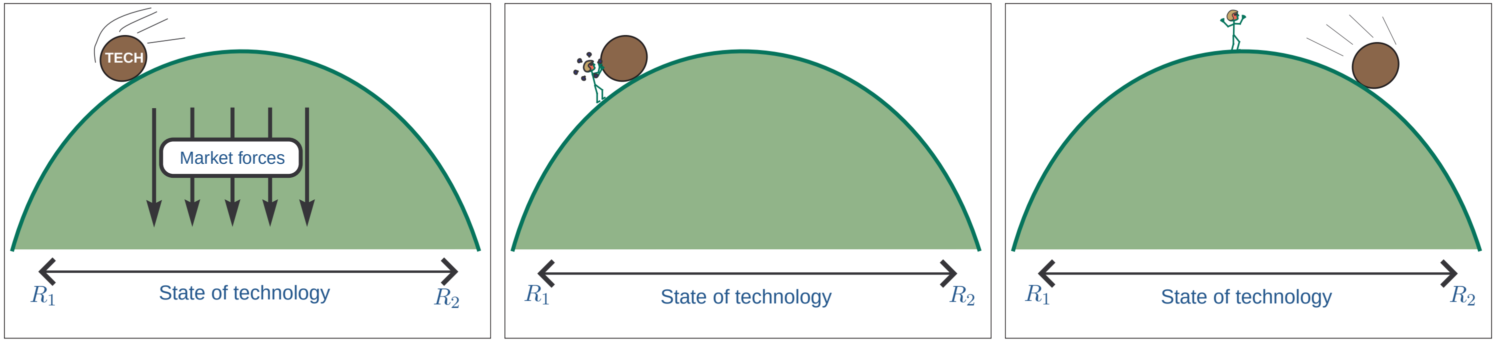


Figure 1: Illustration of how relative prices (the shape of the economic landscape) determine the relative levels of technology augmenting clean and dirty inputs in the model, and the role of a regulator.

Policy implications?

Evidence?

What went wrong?

A simple model with alternative resource inputs

We can match data much better with a simple model without any DTC, and fixed elasticities of substitution between alternative resource inputs.

A simple model with alternative resource inputs

Recall: $Y = (A_L L)^{1-\alpha}(A_R R)^{\alpha}$.

$$\max \pi = p_y (A_L L)^{1-\alpha}(A_R R)^{\alpha} - w_l L - w_r R;$$

$$w_r R = \alpha Y.$$

Now $R_t = \left[(\gamma_c A_{ct} X_{ct})^{\epsilon} + (\gamma_d A_{dt} X_{dt})^{\epsilon}\right]^{1/\epsilon}$.

Assume $A_c = A_d = A$, and fix $A_R = 1$.

$$Y_t = (A_t L_t)^{1-\alpha} R_t^{\alpha},$$

$$R_t = A_t \left[(\gamma_c X_{ct})^{\epsilon} + (\gamma_d X_{dt})^{\epsilon}\right]^{1/\epsilon},$$

and $C_t = Y_t - (w_{ct} X_{ct} + w_{dt} X_{dt})$,

A simple model with alternative resource inputs

$$\pi = w_{rt}A_t\left[(\gamma_c X_{ct})^\epsilon + (\gamma_d X_{dt})^\epsilon\right]^{1/\epsilon} - w_{ct}X_{ct} - w_{dt}X_{dt},$$

$$w_c X_c = w_r (R/A)^{1-\epsilon}(\gamma_c X_c)^\epsilon$$

and $$w_d X_d = w_r (R/A)^{1-\epsilon}(\gamma_d X_d)^\epsilon,$$

Raise everything to $1/(1-\epsilon)$ and rearrange to obtain

$$w_c X_c = w_r^{1/(1-\epsilon)}(R/A)(\gamma_c/w_c)^{\epsilon/(1-\epsilon)}$$

and $$w_d X_d = w_r^{1/(1-\epsilon)}(R/A)(\gamma_d/w_d)^{\epsilon/(1-\epsilon)},$$

hence $$\frac{w_c X_c}{w_d X_d} = \left(\frac{\gamma_c/w_c}{\gamma_d/w_d}\right)^{\epsilon/(1-\epsilon)}.$$

This implies that the resource that is cheaper per efficiency unit takes the larger factor share, and the advantage is bigger the higher is the substitutability between the resources (i.e. when $\epsilon \to 1$).

A simple model with alternative resource inputs

$$w_c X_c = w_r^{1/(1-\epsilon)} (R/A)(\gamma_c/w_c)^{\epsilon/(1-\epsilon)}$$

and

$$w_d X_d = w_r^{1/(1-\epsilon)} (R/A)(\gamma_d/w_d)^{\epsilon/(1-\epsilon)}.$$

A simple model with alternative resource inputs

$$w_c X_c = w_r^{1/(1-\epsilon)}(R/A)(\gamma_c/w_c)^{\epsilon/(1-\epsilon)}$$

and

$$w_d X_d = w_r^{1/(1-\epsilon)}(R/A)(\gamma_d/w_d)^{\epsilon/(1-\epsilon)}.$$

Because we have perfect markets, price equals unit cost so

$$\begin{aligned} w_r &= (w_c X_c + w_d X_d)/R \\ &= w_r^{1/(1-\epsilon)}(1/A)\left[(\gamma_c/w_c)^{\epsilon/(1-\epsilon)} + (\gamma_d/w_d)^{\epsilon/(1-\epsilon)}\right] \\ &= \left\{A/[(\gamma_c/w_c)^{\epsilon/(1-\epsilon)} + (\gamma_d/w_d)^{\epsilon/(1-\epsilon)}]\right\}^{\epsilon/(1-\epsilon)}. \end{aligned}$$

A simple model with alternative resource inputs

So we have

$$w_r = \left\{ A / [(\gamma_c/w_c)^{\epsilon/(1-\epsilon)} + (\gamma_d/w_d)^{\epsilon/(1-\epsilon)}] \right\}^{\epsilon/(1-\epsilon)}.$$

And since $w_r R = \alpha Y$ we have

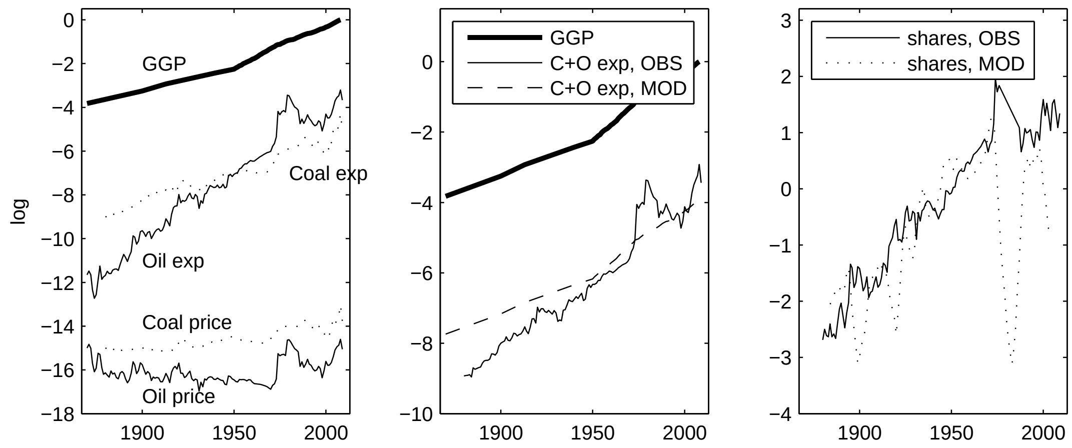
$$w_r = \alpha (AL/R)^{1-\alpha},$$

and we can eliminate w_r to yield

$$R = AL \left\{ \alpha [(\gamma_c/w_c)^{\epsilon/(1-\epsilon)} + (\gamma_d/w_d)^{\epsilon/(1-\epsilon)}] \right\}^{1/(1-\alpha)}.$$

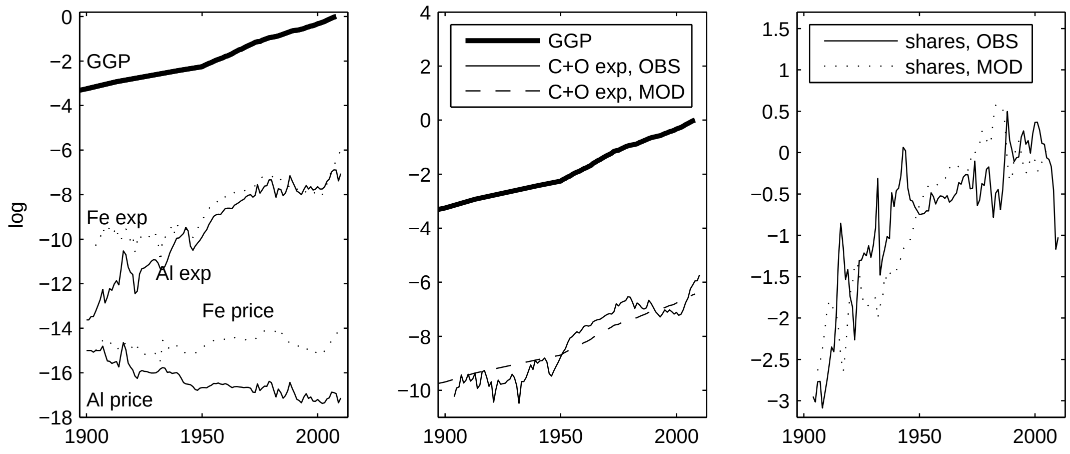
So if w_c and w_d are both constant then R grows at the same rate as Y, i.e. $g + n$, the sum of the growth rates of labour productivity and population.

A simple model with alternative resource inputs



Long-run growth in prices and factor expenditure, compared to growth in global product, for crude oil and coal, and a test of the model. In the left-hand figure we see observed prices and expenditures, with expenditures compared to global product. In the middle figure we see observed total expenditure on coal and oil, compared to the model prediction (based on the prices). And in the right-hand figure we see the observed relative factor shares of coal and oil, compared to the model prediction. In the calibrated model we have $\alpha = 0.02$, $\gamma_c/\gamma_d = 0.55$, and $\epsilon = 0.76$.

A simple model with alternative resource inputs



Long-run growth in prices and factor expenditure, compared to growth in global product, for iron and aluminium, and a test of the model. In the left-hand figure we see observed prices and expenditures, with expenditures compared to global product. In the middle figure we see observed total expenditure on iron and aluminium, compared to the model prediction (based on the prices). And in the right-hand figure we see the observed relative factor shares of iron and aluminium, compared to the model prediction. In the calibrated model we have $\alpha = 0.002$, $\gamma_c/\gamma_d = 50$, and $\epsilon = 0.55$.

Summing up on DTC

Implications

Recall that investment in input-augmenting knowledge is expected to be in proportion to the factor share of the input.

This should help to deal with resource scarcity, as we learn to economize on scarce resources which rise in price and take a greater factor share. It is one way in which the economy can adapt.

With regard to substitution between resources, the implications are potentially dramatic. A resource which is not currently competitive will attract little investment from short-sighted firms (because of its low current share). If we have *independent knowledge stocks* then its competitiveness will decline even further. If it is the best long-run option there may be a need for policy to encourage research into this resource from a far-sighted regulator. But we don't have independent knowledge stocks!

Structural change, composition effects, and rebound

Background

Background

- Growth and structural change.
- Why we need changes in the composition of consumption to explain energy data.
- Driving forces of such changes.
- Why it matters.

Background

See Sager (2019) on CO_2 emissions, technology, and the composition of consumption.

Sager's figure 2 shows how the CO_2 content of the average US household's consumption was pretty flat over the 15-year period he studies, but that with fixed technology (i.e. fixed emissions intensities) and all else equal, emissions would have risen by 50 percent.

This shows the powerful reduction in emission intensities through technological progress.

Background

See Sager (2019) on CO_2 emissions, technology, and the composition of consumption.

From Sager's figure 3 (bottom right panel) we can see that fixing both technology and expenditure, emissions are around 40 percent higher for the 2009 consumption basket than they are for the 1996 basket. This isolates the effect of the change in composition.

The rebound effect

The rebound effect

The idea of rebound dates back to Jevons (1865), who argued that future scarcity of coal would be exacerbated, not alleviated, by innovations increasing the efficiency of technologies based on coal use, the reason being that such innovations would lead to a large increase in the use of coal-based technologies.

The idea has been picked up more recently by energy and ecological economists (see for instance Binswanger, 2001), where it has been named the rebound effect.

To define rebound, assume an economy in which total energy use is R, and focus on production of good i using (among other inputs) augmented energy flow $A_{ri}R_i$. Rebound is present when an increase in energy-efficiency A_{ri} by a factor x leads to a reduction of R by less than $R_i(1-1/x)$.

The rebound effect

Both income and substitution effects may contribute to rebound.

An increase in A_{ri} leads (ceteris paribus) to a fall in the price of good i, which raises the purchasing power of consumers (income effect) and induces them to substitute towards consumption of good i (substitution effect).

Given the small factor share of energy, the income effect of increases in energy-augmenting technology is likely to be small; on the other hand, given the much higher energy share of some products, the substitution effect of increases of the energy-efficiency of such products may be substantial.

The rebound effect

The more powerful is the rebound effect, the less effective are increases in the energy-efficiency of technology in actually reducing energy use. Policy relevance!

Substitution effects

Substitution effects

Two products, Y_1 and Y_2. Perfect markets.

$$Y_1 = \gamma_L A_L L;$$
$$Y_2 = \gamma_R A_R R.$$

Thus labour is the only input to Y_1, and energy is the only input to Y_2.

Aggregate production:

$$Y = (\alpha Y_1^\epsilon + (1-\alpha) Y_2^\epsilon)^{1/\epsilon}. \tag{1}$$

Thus when ϵ is negative the two aggregate products are complements in the sense that if a product becomes increasingly scarce then its factor share rises.

Substitution effects

Let labour L and the ratio of the input prices, w_R/w_L, evolve exogenously, and derive total energy use R from the model.

The solution is straightforward. Briefly, derive two different expressions for the ratio of the prices of the aggregate goods: firstly by comparing their marginal contribution to Y, and secondly by comparing their unit production costs. Use these two expressions to eliminate the price ratio, and rearrange to show that

$$\frac{R}{L} = \left[\frac{1-\alpha}{\alpha} \left(\frac{\gamma_R A_R}{\gamma_L A_L} \right)^{\epsilon} \left(\frac{w_R}{w_L} \right)^{-1} \right]^{1/(1-\epsilon)} .$$

Hence the aggregate elasticity of substitution between energy and labour is $1/(1-\epsilon)$.

Substitution effects

$$\frac{R}{L} = \left[\frac{1-\alpha}{\alpha}\left(\frac{\gamma_R A_R}{\gamma_L A_L}\right)^{\epsilon}\left(\frac{w_R}{w_L}\right)^{-1}\right]^{1/(1-\epsilon)}.$$

Now set $\epsilon = 0$. This implies that equation 1 is Cobb–Douglas, and the aggregate elasticity of substitution between energy and labour is 1. Thus we have the constant-share result and 100 percent rebound (energy demand is not affected by the direction of technological change)! The result is intuitive: we have two products, one made entirely using labour, the other using only energy. When the products are combined in a Cobb–Douglas function on the consumption side the products take constant shares, and therefore labour and energy must also take constant shares.

Substitution effects

So in this economy, boosting A_R doesn't help to reduce energy demand. But what happens if we tax energy use?

Income effects

Income effects

Income effects are tricky to include in macroeconomic models, especially in combination with price changes; the models become a lot less tractable. See Boppart (2014) for a model which manages this combination.

We opt for an extremely simple model with *lexicographic preferences* instead.

Income effects

Assume an economy with a series of products Y_1, Y_2, Y_3, etc. The price of Y_i is denoted p_i, and $p_i = 2^{i-1}$. So $p_1 = 1$, and product $i+1$ is twice as expensive as product i.

Energy use E_i per unit of product Y_i is as follows: $E_i/Y_i = \alpha 2^{2(i-1)}/A$, where α is a parameter and A is productivity. So product $i+1$ is four times as energy-intensive as product i, but only twice as energy-intensive per dollar spent.

A is labour productivity as well as labour productivity (they grow at equal rates). Furthermore, the annual wage is also equal to A. A doubles each period (30 years). In the first period, $A = 1$.

Energy costs are a small part of total costs.

Income effects

Workers (wage A per year) demand at least one unit of consumption per year, and choose the most expensive product they can afford under this restriction (lexicographic preferences).

- What product do they choose in period 1?
- What product do they choose in period 2?
- What is energy use in periods 1 and 2?
- What would happen to energy use in period 2 is workers stuck with product 1 rather than 'trading up'?
- What is the effect of an energy tax, given that energy costs are a small part of total costs?
- What is the effect of an exogenous increase in α, energy efficiency?
- Rebound?

Income effects

Rebound occurs when (for instance) a 10 percent increase in energy efficiency does not give a 10 percent *decrease* in energy use. In the above economy there is almost no rebound. (Why is there any at all?) The reason is that increases in energy demand are driven entirely by *income effects*.

What, if anything, can we learn from the 'model'?

Reality?

Reality?

So we have two models, one based entirely on income effects with no rebound, and one based entirely on substitution effects with 100 percent rebound. Now we need some evidence!

See Hart (2018).

Reality?

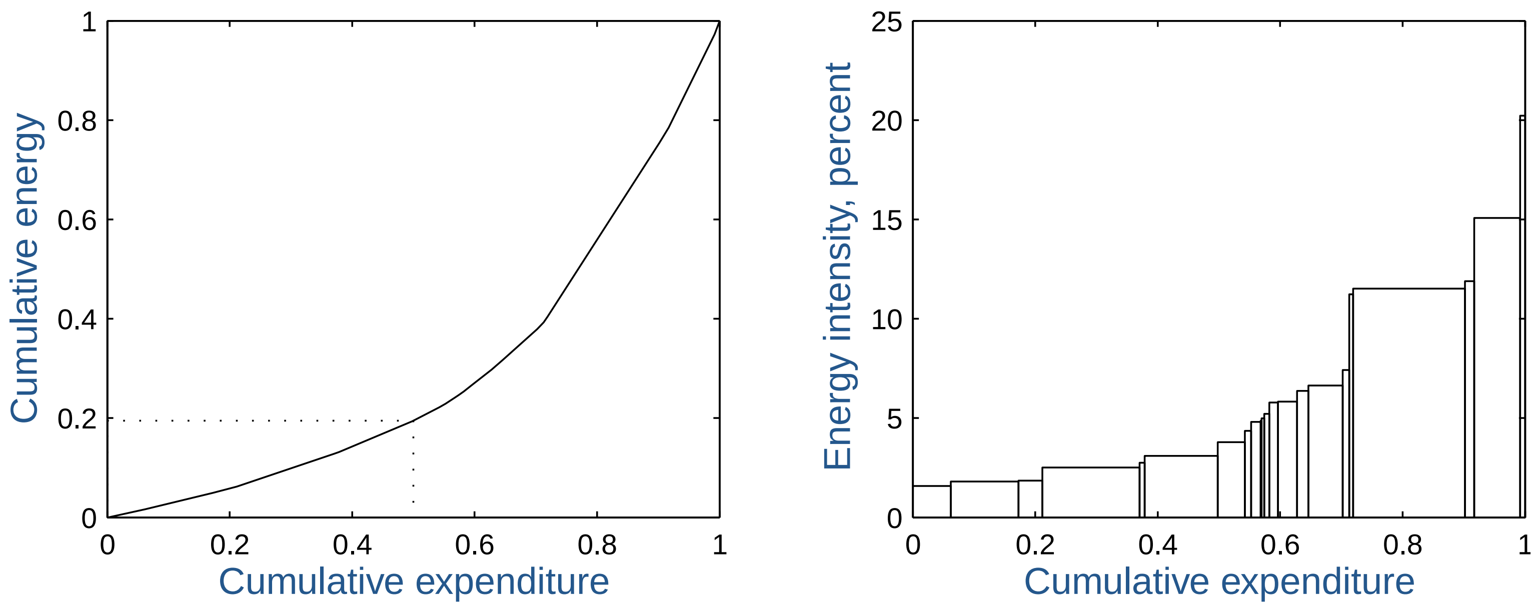


Figure 2: Cumulative energy use and energy intensity plotted against cumulative expenditure when consumption products are sorted in order of increasing energy intensity. All the axes are normalized. Regarding energy intensity, we only have data on relative intensities, and we normalize to give an average intensity of 4 percent. For sources see Hart (2018).

Reality?

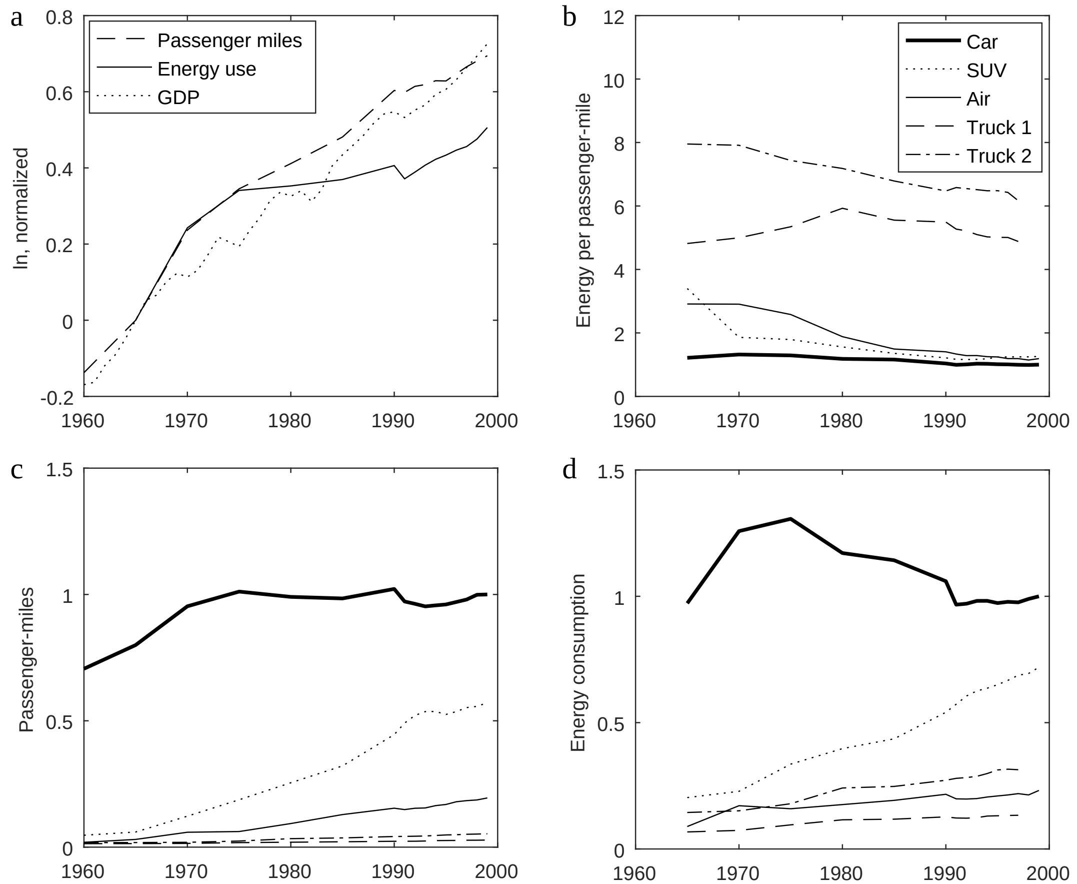


Figure 3: Aggregate data for passenger-miles and energy consumption in the U.S. for private vehicles and air travel (combined). For sources see Hart (2018).

Reality?

Reality is messy! We have a broad range of products consumed, none of which is all that energy intensive (up to approximately 20 percent expenditure on energy). So clearly our model based on substitution effects is way off. But so is the model based only on income effects, in which we consume one product at a time.

Much more work is needed to build a picture of past developments and the future.

Air travel. Our work (Stråle 2021, Tourism Economics) suggests that the income elasticity of demand for air travel is very high—around 3—hence income effects seem to be powerful. At the same time, the real price of long-distance air travel has fallen by around 2 percent per year, so a relatively modest elasticity of substitution between air travel and other goods could also explain a lot of the shift.

Reality?

Note that the price fall of air travel is not just driven by increasing fuel efficiency, but to a greater extent by the increasing efficiency of the entire operation.

What happens when A_L rises faster for energy-intensive goods than for labour-intensive goods? 'Rebound'?

Social norms

Social norms

The majority of economic analysis is based on household utility functions like $u = f(c)$, if we let c include things like consumption goods, environmental quality, and leisure.

What are the implications if our utility from consuming some good is actually a function, not just of *our* consumption of that good, but also of *others'* consumption of it?

This links to ideas such as *social norms*, and also *conspicuous consumption* and *keeping up with the Joneses*. Could our shift into energy-intensive goods be to some extent the consequence of a zero-sum status game?

We return to these ideas later in the course.

Conclusions on resource scarcity and Solow's mechanisms

The mechanisms taken together, and compared

The mechanisms taken together, and compared

The first conclusion is that all the mechanisms together help to hold the overall factor share of natural resources and energy approximately constant, explaining the fit of the Cobb–Douglas function to the long-run data.

If the factor share of natural resources goes up, over time any or all of the three mechanisms can kick in, helping to bring it back down again. For instance, if the price of aluminium were to rise steeply, that would increase the overall factor share of metals. But firms economizing on aluminium and shifting to alternative metals, and falling quantity of aluminium-based products, would all tend to counter this effect.

The mechanisms taken together, and compared

Which mechanism is most powerful? Jevons paradox tells us that efficiency in a resource and shifts in composition towards that resource tend to go together, which diminishes the overall effect of efficiency increases on resource demand. And in the data we see that huge efficiency increases are often associated with huge increases in quantity (as with lighting).

At the same time we know that consumers are typically relatively insensitive to price increases when it comes to large categories of consumption (as opposed to for instance switching between brands), and that resources typically only make up a fairly small part of the prices of most goods.

The mechanisms taken together, and compared

Therefore it is not surprising to see that switches between resources are where we see the most dramatic shifts. This mechanism is the most powerful! When aluminium gets more expensive, we shift to alternative metals to a much greater extent than we learn to use aluminium more efficiently or shift out of products that require aluminium.

Policy

Policy

What are the policy implications of all this?

Not that amazing. . .

As long as there are well-defined property rights over resources...

Policy

OK, if the interest rate is not socially optimal this could be a problem... but how to solve that!?

If knowledge stocks grow (relatively) independently then if we had a resource which we knew was running out there would be a need for big subsidies to R&D into alternative (substitute) resources.

Firms will not do enough such research on their own because the short-term returns are too low; given independent knowledge stocks it takes a long effort to bring the new resource 'up to speed'.

But knowledge stocks do not grow independently . . .

Policy

So why spend all this time on natural resources if there are no major policy issues?

This understanding is an essential foundation for understanding pollution, and also biodiversity (but that is not covered in this course).