Answers to Written Exam Economics Winter 2020-2021

Advanced Economics of the Environment and Climate Change

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Answers only in English.

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Exercise 1. Environmental regulation and inequality (indicative weight: 3/4)

Generally about this exercise: This exercise builds on a modified version of the model presented by Klenert and Mattauch (2016). Compared to the original model, labor supply is now exogenous which simplifies the model. On the other hand, a pollution externality and a public good are added, increasing the complexity of the model. Finally, the linear tax cut variable is removed from the model.

Consider a small market economy with N households indexed $i = 1, 2, ..., N$. Households supply labor inelastically. Units are chosen such that each household supplies one unit of labor.

The households differ in their productivity. The effective labor supplied by household i is given by the labor supply (which equals one) multiplied by the productivity measure ϕ_i. These productivity measures are normalized such that:

$$\sum_{i=1}^{N} \phi_i = 1.$$

Accordingly, the effective labor supply of the entire economy equals one.

Household i's wage income, I_i, is given by:

$$I_i = \phi_i w(1 - \tau_w^0), \tag{1}$$

where w is an exogenous (average) wage rate, and τ_w^0 is the pre-reform wage tax.

The utility of household i is given by:

$$U = C_i^{\alpha}(D_i - D_0)^{\beta} - \kappa D + \lambda \bar{G},$$

$$0 < \alpha < 1, \quad 0 < \beta < 1, \quad \alpha + \beta = 1, \quad \kappa \geq 0, \quad \lambda \geq 0,$$

where C_i measures consumption of non-polluting goods, D_i measures the consumption of polluting goods, $D_0 > 0$ is the subsistence level (minimum-consumption requirement) for polluting consumption, D is aggregate pollution emission (from domestic territory), and $\bar{G}$ is a public good provided by the government. In the pre-reform scenario there is no public good: $\bar{G} = 0$.

The budget constraint of household i is given by:

$$C_i p_C + D_i p_D(1+\tau) = L_i + I_i,$$

where p_C and p_D are exogenous prices on non-polluting and polluting goods, respectively, τ is the ad valorem pollution tax, and L_i is a lump-sum transfer. In the pre-reform scenario there is no pollution tax and no lump-sum transfer: $\tau = L_i = 0$.

Each household maximizes utility, U, subject to the budget constraint taking all prices, policies, and aggregate variables as given. All households have an income that allow them to purchase more than just the subsistence level of polluting goods.

The government's budget constraint is given by:

$$G + \bar{G} + \sum_{i=1}^{N} L_i = \sum_{i=1}^{N} \tau p_D D_i + \sum_{i=1}^{N} \tau_w^0 \phi_i w,$$

where G is a fixed spending requirement of the government. The equation states that the government's spendings (left-hand side) equals the government's tax revenue (right-hand side).

The consumption of polluting goods results in pollution emissions. Units are chosen such that consuming one unit of the polluting good results in one unit of pollution emission. Hence aggregate pollution emission equals the total consumption of polluting goods:

$$D = \sum_{i=1}^{N} D_i.$$

Finally, define *actual disposable income* as:

$$\bar{I}_i \equiv \phi_i w(1-\tau_w^0) + L_i - D_0 p_D(1+\tau).$$

The actual disposable income is the disposable income left after purchasing the subsistence level of polluting goods.

Question 1.1

Show that solving the problem of household i implies that:

$$C_i = \frac{\alpha}{p_C}\bar{I}_i, \quad \text{and} \quad D_i = \frac{\beta}{p_D(1+\tau)}\bar{I}_i + D_0.$$

Answer to Question 1.1: There are several ways to arrive at these expressions. The key insight is that each household maximizes utility, U, subject to the budget constraint taking all prices, policies, and aggregate variables as given. This is stated directly in the model description.

Each household solves the problem:

$$\max_{C_i, D_i} C_i^\alpha (D_i - D_0)^\beta - \kappa D + \lambda \bar{G}$$
$$\text{st.} \quad C_i p_C + D_i p_D (1+\tau) = L_i + I_i$$

The Lagrangian associated with the problem is:

$$\mathscr{L} = C_i^\alpha (D_i - D_0)^\beta - \kappa D + \lambda \bar{G} + \eta \left(L_i + I_i - C_i p_C - D_i p_D (1+\tau) \right),$$

where η is the shadow price of income.

The first-order conditions amount to:

$$\alpha C_i^{\alpha-1} (D_i - D_0)^\beta - \eta p_C = 0$$
$$\beta C_i^\alpha (D_i - D_0)^{\beta-1} - \eta p_D (1+\tau) = 0.$$

Combining these two equations:

$$C_i = (D_i - D_0) \frac{\alpha}{\beta} \frac{p_D (1+\tau)}{p_C}. \tag{i}$$

Substituting (i) into the budget constraint:

$$L_i + I_i - \underbrace{(D_i - D_0) \frac{\alpha}{\beta} p_D (1+\tau)}_{C_i p_C} - D_i p_D (1+\tau) = 0 \quad \Leftrightarrow$$
$$D_i - D_0 = \frac{\beta}{p_D (1+\tau)} \left(I_i + L_i \right) - \beta D_0,$$

where it is used that $\beta + \alpha = 1$.

Substituting the expression for $D_i - D_0$ into (i):

$$
\begin{aligned}
C_i &= \left[\frac{\beta}{p_D(1+\tau)}\left(I_i + L_i\right) - \beta D_0\right]\frac{\alpha}{\beta}\frac{p_D(1+\tau)}{p_C} \\
&= \frac{\beta}{p_D(1+\tau)}\left[I_i + L_i - p_D(1+\tau)D_0\right]\frac{\alpha}{\beta}\frac{p_D(1+\tau)}{p_C} \\
&= \frac{\alpha}{p_C}\left[I_i + L_i - p_D(1+\tau)D_0\right] \\
&= \frac{\alpha}{p_C}\bar{I}_i.
\end{aligned}
$$

Combining this expression with (i) to eliminate C_i:

$$
\begin{aligned}
\frac{\alpha}{p_C}\bar{I}_i &= (D_i - D_0)\frac{\alpha}{\beta}\frac{p_D(1+\tau)}{p_C} \quad \Leftrightarrow \quad D_i - D_0 = \frac{\beta}{p_D(1+\tau)}\bar{I}_i \quad \Leftrightarrow \\
D_i &= \frac{\beta}{p_D(1+\tau)}\bar{I}_i - D_0.
\end{aligned}
$$

Alternatively, one can leave out the pollution externality and the public good from the utility function and use the monotonic transformation $\tilde{U} \equiv \ln(U)$ to solve the household's problem. The problem is then given by:

$$
\begin{aligned}
&\max_{C_i, D_i} \alpha \ln(C_i) + \beta \ln(D_i - D_0) \\
&\text{st.} \quad C_i p_C + D_i p_D(1+\tau) = L_i + I_i.
\end{aligned}
$$

One may derive the two expressions from the two first-order conditions of this problem together with the budget constraint.

Question 1.2

How does the ratio between expenditures on polluting and non-polluting goods depend on income? Discuss how this prediction is aligned with empirical evidence.

Answer to Question 1.2: The ratio between expenditures on polluting and non-polluting goods is given by:

$$
R(\bar{I}_i) \equiv \frac{D_i p_D(1+\tau)}{C_i p_C} = \frac{\beta}{\alpha} + \frac{D_0 p_D(1+\tau)}{\alpha \bar{I}_i}.
$$

It is clear that $R(\bar{I}_i)$ decreases with actual disposable income. And the actual disposable income is monotonically increasing in income.

Accordingly, expenditures on polluting goods decline with income relative to expenditures on non-polluting goods.

As highlighted by Pizer and Sexton (2019), the average U.S. household energy expenditure fraction declines with income. This empirical tendency also roughly holds for motor fuel consumption.

Energy use is often associated with pollution emission. One example is the use of motor fuels which results in both carbon emissions and local air pollution. One can therefore interpret the polluting good as all energy goods or fossil fuels.

Using this interpretation, the model captures the empirical tendency that low income households spend a larger share of their income on polluting goods.

One caveat is the empirical relationship between income and the expenditure share on energy is less clear for other countries, as emphasized by Pizer and Sexton (2019). In the UK, for instance, the expenditure share on motor fuels have a roughly inverted U-shape.

From here we will interpret pollution as air pollution.

Question 1.3

Discuss for which air pollutants it is reasonable to assume $\kappa = 0$ and $\kappa > 0$, respectively. *Hint: the economy is small.*

Answer to Question 1.3: In the first case where κ equals zero, there is no cost associated with pollution emissions. As the economy is small, this is an appropriate assumption for CO_2 emissions. The emissions stemming from a small economy will have little impact on the global climate. Thus, the pollution damage cost of the economy's own carbon emissions on the economy's own citizens will be very small. Accordingly, it can be reasonable to neglect these damage costs in a model analysis.

If κ is strictly positive, there is a cost associated with pollution emissions. This is a reasonable assumption for local air pollutants like NO_x, SO_2, CO, and VOC. These local air pollutants have negative welfare effects like adverse health effects. Hence it would be unreasonable to assume that there would not be damage costs to the economy from the economy's own pollution emissions.

In the case $\kappa > 0$, consumption of the polluting good may also be interpreted as fossil fuel consumption. The reason is that the combustion of fossil fuels causes both carbon emissions as well as emissions of local pollutants. Hence even if the climate change damages to the economy caused by the economy's own carbon emissions are negligible, there may still be a negative effect on welfare from pollution emission.

Define the indirect utility function:

$$V_i(\cdot) = U\left(C_i(\tau_w^0, L_i, \tau, \phi_i), D_i(\tau_w^0, L_i, \tau, \phi_i)\right) - \kappa D(\cdot) + \lambda \bar{G}(\cdot),$$

where V_i, D and $\bar{G}$ are functions of τ_w^0, ϕ_1, ..., ϕ_N, L_1, ..., L_N, and τ.

Consider the case $\kappa = 0$. The government introduces an environmental tax reform. The reform implies that pollution emissions are taxed, $\tau > 0$, and that the entire tax revenue from the reform is transferred back to the households via lump-sum transfers:

$$\sum_{i=1}^{N} L_i = p_D \tau \sum_{i=1}^{N} D_i.$$

All households receive the same lump-sum transfer which amounts to:

$$L = p_D \tau \frac{D}{N}.$$

Question 1.4

Show that the reform is progressive in the sense that $V_i(\cdot)/V_j(\cdot)$ increases compared to the pre-reform scenario, when $\phi_i < \phi_j$. Comment on the interpretation of this measure of relative welfare. *Hint: note that $\kappa = 0$ and $\bar{G} = 0$.*

Answer to Question 1.4: As there is no provision of the public good, $\bar{G}$, and since there is no welfare cost of pollution emission, $\kappa = 0$, the indirect utility function amounts to:

$$V_i(\cdot) = \left(\underbrace{\frac{\alpha}{p_C}\bar{I}_i}_{C_i}\right)^{\alpha} \left(\underbrace{\frac{\beta}{p_D(1-\tau)}\bar{I}_i}_{D_i - D_0}\right)^{\beta} = \left(\frac{\alpha}{p_C}\right)^{\alpha} \left(\frac{\beta}{p_D(1-\tau)}\right)^{\beta} \bar{I}_i,$$

where C_i and D_i are given by the expressions from Question 1.1, and it is used that $\alpha + \beta = 1$.

The utility ratio is then:

$$\frac{V_i(\cdot)}{V_j(\cdot)} = \frac{\phi_i w(1-\tau_w^0) + L - D_0 p_D(1+\tau)}{\phi_j w(1-\tau_w^0) + L - D_0 p_D(1+\tau)}.$$

Define the variables:

$$\begin{aligned} A &\equiv \phi_i w(1-\tau_w^0) - D_0 p_D \\ B &\equiv \phi_j w(1-\tau_w^0) - D_0 p_D \\ t &\equiv L - D_0 p_D \tau. \end{aligned}$$

The ratio before the reform equals A/B. After the reform, the ratio is $(A+t)/(B+t)$.

To prove that the reform is progressive we need to show that:

$$\frac{A}{B} < \frac{A+t}{B+t} \quad \Leftrightarrow \quad AB + At < AB + Bt \quad \Leftrightarrow \quad A < B.$$

The last inequality is always true since $\phi_j > \phi_i$.

A small detail is that the above calculations rely on the assumption that t is always positive. It is easy to show that this is true. If $t > 0$ then:

$$L = p_D \tau \frac{D}{N} > D_0 p_D \tau \quad \Leftrightarrow \quad D - ND_0 > 0 \quad \Leftrightarrow \quad \sum_{i=1}^{N} (D_i - D_0) > 0.$$

The last inequality is obviously true, as the consumption of polluting goods is higher than the subsistence level for all households by assumption.

The welfare measure, $V_i(\cdot)/V_j(\cdot)$, shows the relative utility level of a household i relative to household j which has a higher productivity level. The welfare measure can therefore only tell us about the impact of the reform on the relative utility levels. Importantly, the measure does not show whether household i is better of after the reform.

If the welfare measure increases due to a reform, the utility of household i increases relative to richer households. Assuming that utility is cardinal, as we do in this exercise, this means that the reform places a relatively higher welfare burden on the rich households.

One may object that since we usually interpret the utility level as ordinal (not cardinal), the welfare measure does not tell us anything about the change in relative welfare. Thus we have implicitly conducted a cardinal utility interpretation in line with Klenert and Mattauch (2016).

Question 1.5

How does the reform affect income inequality between household i and j (still assuming $\phi_i < \phi_j$)? Use the relative income between household i and j before and after the reform to answer the question. Briefly explain the intuition.

Answer to Question 1.5: The income of household i before the reform was: $\phi_i w(1-\tau_w^0)$. Thus the relative income of household i and j amounts to ϕ_i/ϕ_j before the reform. After the reform the income is: $\phi_i w(1-\tau_w^0) + L_i$. Accordingly, placing relative income before the reform on the left-hand side of the inequality and relative income after the reform on the right-hand side:

$$\frac{\phi_i}{\phi_j} = \frac{\phi_i w(1-\tau_w^0)}{\phi_j w(1-\tau_w^0)} < \frac{\phi_i w(1-\tau_w^0) + L_i}{\phi_j w(1-\tau_w^0) + L_j}.$$

If this inequality is true, the reform has reduced income inequality. To evaluate the expression, define the variables:

$$\tilde{A} \equiv \phi_i w(1-\tau_w^0)$$
$$\tilde{B} \equiv \phi_j w(1-\tau_w^0).$$

Evaluating the reduced expression (using the fact that the lump-sum transfer is the same for all households):

$$\frac{\tilde{A}}{\tilde{B}} < \frac{\tilde{A}+L}{\tilde{B}+L} \quad \Leftrightarrow \quad \tilde{A} < \tilde{B}.$$

As the last inequality is true by assumption, the reform reduces income inequality.

Intuitively one can explain the result as follows. The wage income is independent of the pollution tax in this partial equilibrium framework. Thus, the reform only affects income through the lump-sum transfer. Since the lump-sum transfer is the same for all households, it will have a relatively larger effect on the income of relatively poorer households. Thus, the income inequality - measured as relative income - will shrink due to the lump-sum transfer.

An unimportant detail is that income equals expenditures in this static framework without savings. The expenditure inequality - measured as relative expenditures - would therefore also shrink.

Through the remaining part of this exercise, consider the case $\kappa > 0$ and $\lambda > 0$, and the following environmental tax reform. The government introduces a tax on pollution emission: $\tau > 0$. The tax revenue is used for two purposes.

Firstly, the government provides a lump-sum transfer to all households that covers additional expenditures on the subsistence level of polluting consumption imposed by the pollution emission tax:

$$L_i = L = p_D \tau D_0.$$

The total cost of this transfer is:

$$\sum_{i=1}^{N} L = NL = N p_D \tau D_0.$$

Secondly, the government uses the remaining revenue to finance a public good. This implies that:

$$\bar{G} = \underbrace{p_D \tau \sum_{i=1}^{N} D_i}_{\text{Total tax revenue}} - \underbrace{N p_D \tau D_0}_{\text{Cost of transfer scheme}} = p_D \tau \sum_{i=1}^{N} (D_i - D_0).$$

One can show that aggregate pollution emission after the reform is given by:

$$D = \frac{\beta w (1 - \tau_w^0)}{p_D (1 + \tau)} + N D_0 \left(1 - \frac{\beta}{1 + \tau}\right).$$

You can take this result as given.

Question 1.6

Show that aggregate pollution emission is declining in the pollution tax τ. Explain the role of the subsistence level of polluting consumption.

Answer to Question 1.6: Differentiating aggregate pollution emission by the pollution tax rate:

$$\begin{aligned}\frac{\partial D}{\partial \tau} &= \frac{\beta w (1 - \tau_w^0)}{p_D} (-1) \frac{1}{(1 + \tau)^2} - \beta (-1) \frac{1}{(1 + \tau)^2} N D_0 \\ &= \frac{\beta \left[N D_0 p_D - w (1 - \tau_w^0) \right]}{p_D (1 + \tau)^2}.\end{aligned}$$

Clearly,

$$\frac{\partial D}{\partial \tau} < 0 \quad \Leftarrow \quad w(1-\tau_w^0) > ND_0 p_D.$$

The last inequality is true, and thus, aggregate pollution emission is decreasing in the pollution tax, as expected. To see this, consider the wage income and the expenditures on the subsistence level on the polluting goods before the reform. By assumption, income is higher than this subsistense expenditure level:

$$\phi_i w(1-\tau_w^0) > D_0 p_D.$$

Summing over all households:

$$\sum_{i=1}^{N} \phi_i w(1-\tau_w^0) = w(1-\tau_w^0) > \sum_{i=1}^{N} D_0 p_D = ND_0 p_D.$$

This proves that the inequality is true and that aggregate emissions are decreasing in the emission tax.

When it comes to the role of the subsistence level of polluting consumption, it is clear that a higher subsistence level reduces the derivative of D with respect to τ. Accordingly, a higher subsistence level implies that aggregate pollution emission reacts less to changes in the pollution tax rate.

The reason is that as the pollution tax increases, households reduce their purchases of polluting consumption goods. But, they will not change their subsistence purchases. Thus, a higher subsistence level implies that there is a larger consumption of polluting goods which is unaffected by the pollution tax. This makes aggregate pollution less responsive to changes in the pollution tax rate.

The optimal emission tax for household i given the transfer scheme, denoted τ_i^*, can be derived from the problem:

$$\max_{\tau} \left(\frac{\alpha}{p_C}\right)^{\alpha} \left(\frac{\beta}{p_D(1-\tau)}\right)^{\beta} \bar{I}_i - \kappa D + \lambda \bar{G}.$$

It can be shown that τ_i^* can be expressed as:

$$\tau_i^* = \left[\frac{\beta \left(\lambda + \kappa / p_D\right) \sum_{i=1}^{N} \bar{I}_i}{\left(\frac{\alpha}{p_C}\right)^{\alpha} \left(\frac{\beta}{p_D}\right)^{\beta} \bar{I}_i} \right]^{\frac{1}{1-\beta}} - 1.$$

You can take this expression as given.

Question 1.7

Do the households agree on the optimal emission tax level given the transfer scheme? Explain the intuition.

Answer to Question 1.7: The optimal pollution tax depends on actual disposable income, $\bar{I}_i$, which differs between all household. Thus, the households do not agree on the optimal pollution tax level.

It is clear the optimal tax level decreases with the actual disposable income as $0 < \beta < 1$. Thus, the relatively poorer households prefer a relatively higher pollution tax.

Intuitively, this can be explained the following way. The reform provides two public goods: emission reductions and the other public good. All households receive the same benefit from these public goods.

In addition, the reform increases the cost of polluting consumption goods. Seen in isolation, this hits the relatively poorer households harder, as they spend a relatively larger fraction of their income on polluting consumption. This is a consequence of the subsistence level of polluting consumption.

Furthermore, the households receive a lump-sum transfer that covers their expenditures on the subsistence level of polluting consumption. This implies that all households are compensated for the additional expenditures imposed by the pollution tax on the subsistence level of polluting consumption. The change in relative prices therefore hit all households equally hard.

All in all, the public good benefit is the same for all households, while the households are compensated for their additional expenditures on the subsistence level of polluting consumption. As the relatively richer households pay relatively more for the reform, but receive the same benefits as the relatively poorer households, they would prefer a relatively lower pollution tax.

Question 1.8

Evaluate the usefulness of this model in terms of analyzing equity (or inequality) issues related to environmental tax reforms. Your evaluation should focus on mechanisms that are absent in the model.

Answer to Question 1.8: This question can be answered in multiple ways. But a good answer will include some of the following critical points about the model.

As the model is a partial equilibrium model, it is missing the direct effects of an environmental tax reform on prices. One would expect that an environmental tax reform affects the entire price system. The question is then if these effects are important.

Alternatively, the model can be interpreted as a general equilibrium model with labor as the only production factor, constant returns to scale production technologies, and perfect competition. However, even in this case, the simplicity of the production structure implies that changes to the pollution tax does not affect prices which seems unrealistic.

In addition, the model does not feature capital and natural resources. An environmental tax reform may reduce the returns to both capital and natural resource investments. The use of capital is, for instance, typically associated with pollution emission. An environmental tax reform may therefore reduce the capital level in the economy which affects labor productivity and thereby wages. On top of that, there may not be a complete pass through of additional production costs to consumer prices, placing a higher cost burden on capital owners - typically high income households. Leaving this mechanism out may exaggerate the regressiveness of an environmental tax reform (Pizer and Sexton 2019).

It is also worth emphasizing that the present model holds the labor supply fixed. An environmental tax reform that distorts relative prices is likely to affect the labor supply as well. If households respond heterogeneously in terms of labor supply to an environmental tax reform, that will affect income inequality.

One may come up with more general equilibrium effects, but the effects mentioned above seem like the most important.

Although several potentially important mechanisms are absent in the present modelling framework, one may argue that the model provides a useful starting point for an analysis of equity issues related to an environmental tax reform.

Exercise 2: The connection between the Hotelling rule and the Green Paradox hypothesis (indicative weight: 1/4)

(Hint: You may provide purely verbal answers to the questions in this exercise, but you are also welcome to include equations if you find it useful)

Question 2.1

Briefly explain the Hotelling rule.

Answer to Question 2.1: The Hotelling rule is an optimality condition associated with the portfolio choice problem of an owner of an exhaustible resource. The two key assumptions are that: (1) the resource owner optimizes the net present value of his/her profit stream, and (2) the exhaustible resource is scarce over the time horizon of the maximization problem.

The resource owner has two options. Firstly, he/she can extract resources today, sell them, and invest the revenue in other types of capital. Secondly, he/she can postpone extraction and sell the resources at the future price. The Hotelling rule implies that the optimal choice of the resource owner is to extract resources to an extent where the returns to these two activities equalize. This is achieved when the relative increase in the resource rent equals the rate of return on capital.

Question 2.2

Discuss how the Hotelling rule is connected to the Green Paradox hypothesis. Discuss how the empirical validity of the Hotelling rule affects the validity of the Green Paradox hypothesis. Start your discussion with a brief introduction of the Green Paradox hypothesis.

Answer to Question 2.2: This question can be answered in multiple ways. But a good answer will typically include the main elements of the following line of argument.

According to the Green Paradox, climate policies that are intended to mitigate carbon emissions may in fact accelerate global warming.

When the government tightens the climate policy in a way that reduces the unit price received by the fossil fuel suppliers in the future relative to the present, the suppliers have an incentive to expedite fossil fuel extraction. This leads to a higher short-run supply – and thereby consumption – of fossil fuels, which accelerates global warming.

The Green Paradox hypothesis relies on two features of the optimization problem of the fossil fuel extractors: (1) fossil fuel extractors optimize the net present value of their profit streams, and (2) the fossil fuel stocks are scarce over the time horizon of the maximization problems. Given these features, the optimal behaviour of the fossil fuel extractors is described by a Hotelling rule.

If the fossil fuel extractors do not optimize intertemporally, or if their fossil fuels stocks are not scarce over the relevant time horizon, they will not expedite extraction as a response to changes in intertemporal prices caused by changes in the climate policy. In that sense, both the Green Paradox and the Hotelling rule are consequences of the two features of the optimization problem mentioned above.

One should therefore expect that if there is a Green Paradox, fossil fuel extractors would act according to some type of Hotelling rule. Thus the empirical validity of the Green Paradox appears contingent of the empirical validity of the Hotelling rule.

The empirical literature offers little evidence supporting the Hotelling rule. This seems to suggest that there is little support for the Green Paradox hypothesis. One the other hand, it is difficult to test the validity of the Hotelling rule, as the rule can take various forms, depending on, for instance, the development of extraction technologies.

References

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