Mandated Energy Efficiency Policy Revisited: Mechanical Effect versus Rebound Effect

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Background

The debate on whether or not energy efficiency improvements can be relied upon to reduce energy consumption and further control emissions of carbon dioxide contributing most to global climate change has lasted for more than a hundred years. In the middle of nineteenth century Jevons first observed that increased efficiency in the use of coal caused the increased consumption of coal in Britain in the 19th century (1865). He argued that, on the contrary of common intuition, technology progress need not result in reduced energy consumption, which was known as the Jevons Paradox. However, after a hundred years, the common belief that energy efficiency means energy saving has become rooted among engineers, physicist and policymakers (Chu & Majumdar, 2012; Lovins, 1976). Based on the understanding of direct mechanical effects of energy efficiency improvement, this belief postulates that, for instance, if the energy efficiency of an automobile doubles, it will lead to a halving demand for fuel. As seen from recent history, energy consumption has been increasing since the 19th century. Little evidence shows that the efficiency improvement led to energy consumption reduction. Why? Partly because those who believe in technology overlook the fundamental mechanism of price change resulting from efficiency improvement. In fact, this optimistic belief on energy efficiency assumes a zero price elasticity of demand, which hardly holds among rational consumers' behaviours (Khazzoom, 1980). Khazzoom questioned the idea that energy saving followed as a consequence of the adoption of increasingly efficient technology. He pointed to the paradox by comparing energy efficiency with production efficiency improvement and his results were heatedly discussed in the 19th century. At that time, some theoreticians considered the efficiency in production would lead to redundant workers, even would set the stage for the destruction of capitalism. Fortunately, that did not come true. The case for energy would be identical to the production efficiency if we change the word "labour" to "energy". The reason why labour or energy is not saved from improved efficiency may be the demand for goods or services increases as a result of decreased effective price implicitly led by a technology implementation, as explained by Khazzoom (1987). Soon after that, in the last decade of 20th century, Brookes (1990) extended Khazzom's conclusion to the macro-level.

Later, Saunders (1992) gives a more sound and rigid theoretical analysis for the macro-level feedback of energy efficiency improvement, employing a neo-classical growth model.

While the first dispute over energy efficiency seems to come to an end in the late nineteen nineties when the conclusion made on technology admits that efficiency can be viewed as a source of energy saving and that the benefits from the technologies can be offset by the evoked behavioural effect by rational agents, another debate on how much the "rebound effect" is arises. The rebound effect, as mentioned above, includes direct (micro-level) and indirect (macro-level) feedback from consumers when per unit of goods or services use less energy. The typology of rebound effect varies among researchers (Berkhout, Muskens, & Velthuijsen, 2000; Greening, Greene, & Difiglio, 2000), the centre of the discussion lies on the direct rebound effect, partly because it is easier to measure empirically. The following years saw a surge of econometric analysis on the rebound effect, covering a wide range of sectors and countries (Chitnis, Sorrell, Druckman, Firth, & Jackson, 2014; Sorrell, Dimitropoulos, & Sommerville, 2009). Not surprising, estimation results on rebound effect vary dramatically partly because different data approaches are selected in different studies. Just as Turner (2013) suggests, "the lack of consensus in the literature is grounded in a rush to empirical estimation in the absence of solid analytical foundations".

Therefore, this paper revisits the rebound effect from*, inter alia*, a neo-classical theoretical perspective, aiming to explain what may happen under different treatment of efficiency improvement and policy implementation and why. Several assumptions, such as competitive markets and rational behaviours, are made to make the analysis possible. First, we derive the optimal amount of unit input, price under a market clearing circumstance in the equilibrium where no technology or policy is implemented in this benchmark model. Then, to see how autonomous efficiency technology and mandatory efficiency standards affect the equilibrium, we set up three scenarios. In the first scenario, we treat the energy efficiency technology exogenously. We assume that the technological shock leads to a reduction in every input proportionally, which is equivalent to say that with the same amount of inputs, the production increases. As the result of efficiency improvement, the unit cost of production decreases. As assumed before, the competitive market ensures that the price of the product decreases. Consequently, the new equilibrium depends on how much the consumption increases, which relies on the price elasticity of demand. To make the analysis more specific, we used a Cobb-Douglas production function with constant returns to scale and assumed that the technology increases the production by φ and price elasticity of demand is η. We define the mechanical effect as a trivial consequence that reduces input requirements when efficiency increases by a small proportion. Therefore, if the optimal unit input for factor i is a_i^0 in the benchmark equilibrium, when efficiency increases by φ, the mechanical effect on factor i will become $\frac{a_i^0}{1+\varphi}$. Certainly this is not the whole story. The efficiency leads to a reduction in price, and lower price induces more consumption. The rebound effect is used to depict this behavioural feedback, consistent with the definitions in previous studies. The demand in the new equilibrium is the demand in the benchmark equilibrium times coefficient $1-\frac{\varphi}{1+\varphi}\eta$. The break-even condition is $\eta = -(1+\varphi)$, which can be interpreted as saying that the rebound effect just offsets the mechanical effect so that efficiency improvement does not cause more demand for input factors, but meets a higher consumption level. In the second scenario, we designed an exogenous technological shock that only reduces one of the required amount of one of the inputs, say, energy. In this case, per unit cost reduces as well resulting to an increased demand for the product. The break-even condition for energy is $\eta = -\frac{1+\varphi}{\alpha}$ which says that the energy would be saved if the value of the price elasticity of demand is greater than the negative inverse of the share of the factor in production. Interestingly, if one input is more efficiently used, requirements for other inputs will always increase to meet the increased demand. In the third scenario, there is a mandatory efficiency standard imposed on one input factor, meaning that this factor (energy again) should be used less and other factors must be more intensively used for producing per unit of goods. This policy increases the cost of production since the firm had minimised its cost in the benchmark model; any other changes in the combination of inputs will cost more to the firm. In the new equilibrium, demand decreases as does energy used since this has been restricted by the mandatory standard. Furthermore, the energy saved should be more than expected from the policy since the decrease in demand corresponds to an increased price. Whether other input requirements are saved relies on the net effect of how elastic the demand is with respect to price and how much more input of each factor is needed to compensate for the energy reduction.

To conclude, the form of the production function, the output elasticities of input factors, and the price elasticity of demand all determine the degree of the rebound effect. Here for simplicity we assumed Cobb-Douglas production function with constant returns to scale. When efficiency in all inputs improves by a small amount, as long as the absolute value price elasticity is smaller than one, fewer resources are required to meet a grown demand. When efficiency improvements happen disproportionally for different input factors, the demand of those factors that are not as efficiently used as others will always increase, regardless of the price elasticity. However for the more efficiently used factor, the absolute value of price elasticity of demand should be equal or smaller than the inverse of the output elasticity of that factor to avoid extra amount of input being required. The third scenario, revealed that a mandated efficiency standards imposes extra cost to the firm, as well as the consumer, thus, less demand for the factor being restricted is ensured. However, since no technology happens, the less use of one demand must be compensated by an increase in another. This may in turn, causes more demand for other input factors.

Finally, several limitations of this paper should be addressed. First, the analysis only looked at the direct rebound effect, and neglects the economic growth related to energy efficiency improvement and the further indirect rebound effect led by economic growth. Potential future research may integrate the neoclassical macroeconomic growth model with energy efficiency improvement. A second limitation is the scenario simulations might be too simple to capture the real world, in particular, when policy implementation and technology improvements happen together. One possible solution is to design another scenario involving both autonomous technological improvement and mandated efficiency policy, and compare what is the optimal policy standard that would balance the mechanical effect and rebound effect. Furthermore, this study does not answer questions about how mechanical effect and behavioural effect might respond to different production functions that differ from Cobb-Douglas. The production of transportation services may be better explained by the Leontief form, when considering the distance travelled under the fuel efficiency improvement that saves fuel not but the labour. However, the analysis in this paper provides a useful theoretical framework for understanding the debate of rebound effect and mandated efficiency standards.

Mechanical effect and rebound effect

The concepts of mechanical and behavioural effects were borrowed from Saez, Slemrod and Giertz (2012), who originally denoted the consequences of income tax change. Though the settings are different, the consequences of technological improvements in efficiency will be best captured by the concepts of mechanical effect and the behavioural effect. Here a mechanical effect depicts a trivial consequence that reduces input demand when efficiency increases by a small proportion, assuming that total production is unchanged. However, observing the reduction in input requirements is not the end of story because cost is also reduced as well as price, if we assume competitive market conditions. Changes in price affect people’s incentives and hence their actual consumption. The price elasticity of demand captures the demand response to price changes. If demand increases due to lower price, supply will also increase to the level that meets demand; thus a new equilibrium is reached. The induced change in demand for the product is defined as behavioural change,

Total effect on input demand

With mechanical and behavioural effects at hand, we can see whether there is a rebound effect by comparing the level of inputs after efficiency improvements with the level of inputs in the original state—without efficiency improvement. Let a_i^0 be the optimal amount of input factor

i that is required to produce one unit of product. Optimal means that this input requirement solves the cost minimization problem (CMP) of the firm. Let q^0 be the equilibrium production that meets the consumption with no shock factor. Now suppose there is an exogenous technological shock that reduces the unit input of i. The input of i becomes a_i^s, under exogenous technological shock that achieves minimum cost. Since cost and price decrease because of less input, consumption will increase to , t—that is, there will be a new equilibrium after technological shock. The rebound effect of input factor i happens only when the total input of i under the new equilibrium, after shock, is greater than the original equilibrium. That is,

$$a_i^s q^s > a_i^0 q^0$$

which is equivalent to

$$\frac{q^s}{q^0} > \frac{a_i^0}{a_i^s}$$

The RHS of the inequality is the change in consumption caused by the behavioural effect, while the LHS is the change in unit input caused by the mechanical effect. The inequality explains that if the behavioural effect is greater than the mechanical effect, more inputs will be required to satisfy the consumption growth. If these effects are equal, consumption grows without the cost of more input. If the mechanical effect outweighs the behavioural effect, inputs will be saved.

The overall effect on inputs, of technological improvements in efficiency, is the difference between the mechanical effect and the behavioural effect, as mentioned above. If the mechanical effect is significant, then a reduction in resources accompanies higher consumption. This is the most ideal case for consumption growth without the cost of the depletion of more resources. If the behavioural effect is dominant, however, efficiency improvement becomes a curse to the economy because more resources are needed to satisfy the huge growth in consumption.

Models for efficiency improvement and mandatory standards

Assumptions and basic settings

Assume the market is competitive. The production function is a Cobb-Douglas form and satisfies constant returns to scale,

$$f(z_1, z_2) = A{z_1}^{\alpha}{z_2}^{\beta}$$

where z_1 and z_2 are input factors, and the constant return to scale implies $\alpha + \beta = 1$. At period zero ($T = 0$), the market is balanced, with production equal to consumption. Let q^o denote the equilibrium production in period zero. The input requirements z_1^0 and z_2^0 solve the CMP of the firm. Let a_1^0 and a_2^0 be the optimal input requirements to produce one unit of the product. Since the market is competitive, price is equal to unit cost. Let p^0 denote the equilibrium price at this production technology. The price elasticity of demand is η.

Scenario 1 Efficiency improvement in all inputs

Suppose in period 1 (($T = 1$), there is an exogenous technological shock that leads to a reduction in every input. The production function becomes $f(z_1, z_2) = (1 + \varphi)A{z_1}^{\alpha}{z_2}^{\beta}$. Thus, the solution for the new CMP for the firm changes the input by only $(1 + \varphi)$. Let z_1^s and z_2^s be the solutions for the CMP, and a_1^0 and a_2^0 be the optimal input requirements to produce one unit of the product under the new technology. Then these must hold:

$$a_1^s = \frac{a_1^0}{1 + \varphi}$$

$$a_2^s = \frac{a_2^0}{1 + \varphi}$$

As defined above, the mechanical effect is

$$\frac{a_i^0}{a_i^s} = 1 + \varphi$$

For $i = 1, 2$ in this model.

The competitive market insures that the new price is

$$p^s = \frac{p^0}{1 + \varphi}$$

Therefore, the percentage change in price is

$$-\frac{\varphi}{1 + \varphi}$$

Given the price elasticity of demand η, the new equilibrium with higher production and consumption induced by the behavioural effect is

$$q^s = (1 - \frac{\varphi}{1 + \varphi}\eta)q^0$$

As defined above, the behavioural effect is

$$\frac{q^s}{q^0} = 1 - \frac{\varphi}{1+\varphi}\eta$$

Now we can check the “rebound effect condition” by comparing the behavioural effect and the mechanical effect. The break-even condition is

$$1 - \frac{\varphi}{1+\varphi}\eta - (1+\varphi) = 0$$

or equivalent to

$$\eta = -(1+\varphi)$$

Here we need to notice that φ is a small number. Therefore when we take the limit of η when $\varphi \to 0$, $\eta = -1$.

The conclusion is that if the absolute value of the price elasticity of demand is smaller than 1, all inputs are saved and the consumption growth rate is exactly $-\eta$. If the absolute value of price elasticity of demand is greater than 1, more resources will be depleted to satisfy the growth of consumption. Finally, if the price elasticity is exactly unity, there is maximized consumption growth without using more resources, either capital or non-capital.

Scenario 2 Efficiency improvements in one input

The analysis is similar to that of Scenario 1. Suppose in period 1 ($(T = 1)$, there is an exogenous technological shock that leads to every input being reduced. The production function becomes $f(z_1, z_2 A) = ((1+\varphi)z_1)^{\alpha} {z_2}^{\beta}$. Thus, the solution for the new CMP for the firm changes the input 1 by only $(1+\varphi)$. Let z_1^t and z_2^t be the solutions for the CMP, and a_1^t and a_2^t be the optimal input requirements to produce one unit of the product under the new technology. Then these must hold:

$$a_1^t = \frac{a_1^0}{1+\varphi}$$

$$a_2^t = a_2^0$$

As defined above, the mechanical effect is

$$\frac{a_1^0}{a_1^t} = 1 + \varphi$$

$$\frac{a_2^0}{a_2^t} = 1$$

The competitive market insures that the new price is

$$p^t = (\frac{\alpha}{1+\varphi} + 1 - \alpha)p^0$$

Therefore, the percentage change in price is

$$-\frac{\alpha\varphi}{1+\varphi}$$

Given the price elasticity of demand η, the new equilibrium with higher production and consumption induced by the behavioural effect is

$$q^t = (1 - \frac{\alpha\varphi}{1+\varphi}\eta)q^0$$

As defined above, the behavioural effect is

$$\frac{q^t}{q^0} = 1 - \frac{\alpha\varphi}{1+\varphi}\eta$$

Now we can check the "rebound effect condition" by comparing the behavioural effect and the mechanical effect. The difference between the scenario here and the first one is that the conditions are different for each of the input factors.

For input factor 1, the break-even condition is

$$1 - \frac{\alpha\varphi}{1+\varphi}\eta - (1+\varphi) = 0$$

or equivalent to

$$\eta = -\frac{1+\varphi}{\alpha}$$

Here we need to notice that φ denotes a small change. Therefore when we take the limit of η, when $\varphi \to 0$, $\eta = -\frac{1}{\alpha}$.

For input factor 2, the break-even condition is

$$1 - \frac{\alpha\varphi}{1+\varphi}\eta - 1 = 0$$

which never holds unless the good is inelastic, if not, the input factor 2 will always increase as long as the price elasticity is negative.

Therefore, if one input is being efficiently used, the other input will always increase. The total effect of the more efficiently used factor would be saved if the absolute value of price elasticity is smaller than the inverse of the share of the factor in production. More inputs are required if the absolute value of elasticity is greater than the inverse of the share in production. There exists no maximum consumption growth rate that sustains the inputs, since the other inputs will always be driven to a higher level.

Scenario 3 Efficiency standards imposed on one input

Suppose there is a mandatory standard imposed on one input factor such that this factor must be more efficiently used, when producing one unit of product. Under this policy setting, the production function becomes

$$Y = A[(1+\bar{\varphi})z_1]^{\alpha}((1+\bar{\varphi})^{-\alpha/\beta}z_2)^{\beta}$$

where $\bar{\varphi}$ is the policy efficiency standard.

The new production function means that without an exogenous technological improvement, when factor 1 is used less, the other input factor must be more intensively used, so that the cost-minimizing input combination is (a_1^p, a_2^p) , which satisfies

$$a_1^p = \frac{a_1^0}{1+\bar{\varphi}}$$

$$a_2^p = (1+\bar{\varphi})^{\alpha/\beta}a_2^0$$

As defined above, the mechanical effects for each of the inputs are

$$\frac{a_1^0}{a_1^p} = 1+\bar{\varphi}$$

$$\frac{a_2^0}{a_2^p} = (1+\bar{\varphi})^{\alpha/\beta}$$

The competitive market insures that the new price is

$$p^p = [\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha)]p^0$$

Notice that $\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha)$ is always greater than or equal to zero (with equality when $\bar{\varphi}$ equals zero), which is intuitive because the original price is the minimum price reached by the CMP.

Therefore, the percentage change in price is

$$\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha) - 1$$

Given the price elasticity of demand η, the new equilibrium with the new production and consumption induced by the behavioural effect is

$$q^p = [\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha) - 1]\eta q^0$$

As defined above, the behavioural effect is

$$\frac{q^p}{q^0} == [\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha) - 1]\eta$$

As before, to check the "rebound effect condition", we need to compare the behavioural effect and the mechanical effect.

For input factor 1, the break-even condition is

$$[\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha) - 1]\eta - (1+\bar{\varphi}) = 0$$

or equivalent to

$$\eta = -\frac{1+\bar{\varphi}}{\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha) - 1}$$

Here we need to notice that $\bar{\varphi}$ denotes a small change. Therefore when we take the limit of η when $\varphi \to 0$, $\eta = -\infty$.

For input factor 2, the break-even condition is

$$[\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha) - 1]\eta - (1+\bar{\varphi})^{-\frac{\alpha}{1-\alpha}} = 0$$

or equivalent to

$$\eta = -\frac{(1+\bar{\varphi})^{-\frac{\alpha}{1-\alpha}}}{\frac{\alpha}{1+\bar{\varphi}} + (1+\bar{\varphi})^{\frac{\alpha}{1-\alpha}}(1-\alpha) - 1}$$

When we take the limit of η when $\varphi \to 0$, $\eta = -\infty$.

The results are not surprising since the mandatory policy in fact enforces an additional cost on the firm. If there is a "rebound effect", then production should not be normal, in the sense that the price elasticity should be positive. Only with a higher response in consumption will demand for the input factor increase. Therefore, we conclude in the third case, that when a standard imposed on one input increases the price, the result is a reduction in both consumption and factor demand. Nevertheless, the demand for both consumption and inputs may increase only when the price elasticity of demand is positive, e.g. a Giffen good.

Disccusion

In the analysis of the interaction between the mechanical effect and the behavioural effect induced by voluntary efficiency improvements and mandatory efficiency improvement standards, we find many interesting results. First, an exogenous technological shock that reduces the same proportion of all inputs may lead to a demand for resources that is either more than, less than or equal to the previous level of resources demand, according to whether the absolute value of price elasticity of demand is greater than, less than or equal to unity. Secondly, if the shock only improves the efficiency of one input factor, the other factor will always be driven to a higher level because the behavioural effect is always greater than the mechanical effect for this factor. The factor that is being efficiently used will be more than, less than or equal to the previous level of demand, depending on whether the absolute value of price elasticity is greater than, less than or equal to the inverse of the share of this input in the production function. The more the share of the input, the less the elasticity needed to outweigh the mechanical effect. Finally, in the third case, where a mandatory standard was promulgated on one input factor, the rebound effect will never occur unless good is not "normal" – i.e., the price elasticity of demand is positive.

The "efficiency curse" phenomenon is not always simple or direct. Assume, for example, that the manufacture of a product requires two inputs—labour and fuel. Then when labour becomes more efficient, a competitive market will ensure that the lower price of the product—a result of the lower labour costs—will increase consumption of, and therefore demand for, the product. This increase will in turn increase production, which will increase the demand for the other input, fuel. This situation—the indirect impact of one input efficiency improvement on another input—has rarely been discussed.

Another question that often generates disagreement and even confusion is whether the more efficient use of an input factor will result in savings or depletion of that factor. To answer this question empirically, it is useful to consider the notion of "mechanical effect" and "behavioural effect". This analysis demonstrates that the behaviour of consumers has a role as crucial as technology development, in saving resources. Reliance on technological improvement alone to eliminate excess atmospheric carbon dioxide may be counterproductive if we neglect the behavioural change induced by market power.

Implications on gasoline demand

Combing with the empirical results, the model will have more implications on gasoline demand. Empirical studies on gasoline demand show that the price elasticity of gasoline demand is around 0.5 in the short run and 1.0 in the long run (see, for example, Melo & Ramli 2014). In the automobile market, consumers may desire the more fuel-efficient automobiles, since they pay less in petrol bills with more fuel-efficient vehicles. The automobile industry has responded to this behaviour with continuous technology development in fuel efficiency, to satisfy consumer demand. This improvement is beneficial in the short run to both the consumer and the environment, because the mechanical effect dominates over the behavioural effect, and less fuel is required for the same amount of consumption. The long-run scenario is more complicated, however. It may be that all input factors are more efficiently used, but to different extents. With a relatively smaller improvement in fuel than other inputs—say, capital—then fuel consumption is destined to grow, as the mechanical effect of fuel is obscure compared to the behavioural effect of increased consumption (more vehicle use).

Furthermore, several empirical studies have demonstrated the insignificance of policies related to fuel-efficiency improvements (Crandall 1992; Mayo & Mathis 1988). The lower vehicle-emission standard in essence forces lower fuel consumption, a result that can be translated into the $\bar{\varphi}$ in the model presented here. Thus, the regulation adds a cost to the producer, which translates to a higher price for the consumer, resulting in no more consumption than before. One of the reasons that such policies have not effectively reduced fuel demand, though, might be that the requirement set by the policy is equal to or smaller than the “exogenous” technological shock. If technology improves faster than the policy’s objective, the product price will decline, causing a return to Scenarios 1 and 2, where if the technological improvement works, but the standard is much higher than the exogenous development, a cost will be imposed on production. The other reason for the ineffectiveness of the emissions standards is that the behavioural effect is a consequence not only of the price effect, but more importantly, of the income effect: consumer income rises, allowing more consumers to buy more of the product. In the model presented here, however, no assumption was made on how consumer income might change over time. This missing income effect is a significant component of the behavioural effect; it contributes to more demand in factor inputs.

Limitations

The first limitation of this model, then, is that it does not take into account the wealth of the consumer. The income or per capita GDP is growing in most countries, albeit at different rates between developed countries and developing countries. Without technological improvements, the growth in income will automatically raise the consumption to a higher level due to the income effect, and input demand will increase. To see whether the cost enforced on the firm through implementing a mandatory policy indeed discourages the consumption, we need to compare the consequences of the consumer stress imposed by the higher price to the consumer satisfaction from the income growth. Consumers might be less influenced by the price change since they are wealthier. As a result, the policy might be ineffective. It is important to integrate this income effect into the research on current policies, to see how much income people are willing to sacrifice to offset the increased stress from mandatory regulations.

The second limitation is the production function. More forms of production function need to be considered, such as the Leontief production function when input factors are not substitutable. Covering more production functions can provide more information to policy makers.

The third limitation is the lack of distinction between short-term and long-term supply. In general, the short-term supply will fix one of the inputs, and only the input that is being efficiently used can be increased in the production process. The situation is more complex than this, however. For example, the firm can make additional profit by increasing production. Yet in the long run, both factors can be selected, depending on the firm's cost minimization problem. Ultimately, therefore, the analysis must take into account both mechanical and behavioural effects.

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