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Eric Maskin

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ARTICLE

Introduction to mechanism design and implementation†

Eric Maskin*

Director, Maskin Research Center of China's Economic Development, Zhejiang University, Hangzhou, PR China

ABSTRACT
This article provides a brief introduction to mechanism design and implementation theory. First, it provides a brief definition of mechanism design. It then provides a few concrete examples that should make clear what the subject is all about.

KEYWORDS
Mechanism design; implementation; Nash equilibrium; game theory

1. Introduction

This article is based on a speech that Professor Maskin gave at Zhejiang University on December 30, 2018. Maskin's speech was converted into this article by Dr. Gaoju Yang from Zhejiang University's Economics School. The abstracts, keywords, title, subtitles, and references were added by the editors for readers' convenience.

As the Nobel Prize site explains (see the Nobel Prize site 2019 and Maskin 2008), in the mid-20th century, economists found themselves in need of a new theoretical framework with which to tackle the comparison of fundamentally different types of economic organisations, such as capitalist and socialist institutions. To do so, along with other scholars, Maskin developed mechanism design and implementation theory for achieving particular social or economic goals.

In this article, Maskin starts with the example of a parent wanting to divide a cake between two children. The goal is to divide the cake in such a way that both children are happy. The mechanism he proposes is to have one child cut the cake in two while the other chooses one of the pieces. In this example, the goal is 'fair division,' and the divide-and-choose mechanism achieves that goal.

2. What is mechanism design?

This article provides a brief introduction to the field of mechanism design. First, we provide a brief definition of the subject. However, the definition may be too abstract to convey much to readers who do not already know mechanism design. So we will provide a few concrete examples that should make clear what the subject is all about.

We can think of mechanism design as the engineering part of economic theory. Most of the time in economics, we look at existing economic institutions and try to explain or predict the outcomes that those institutions generate. This is called the positive or predictive part of economics. Perhaps 80% to 90% of economists do positive economics.

In mechanism design, we do just the opposite by starting with the outcomes. We identify the outcomes we would like to have. And then we work backwards to see whether we can engineer institutions (mechanisms) that will lead to those outcomes. This is the normative or prescriptive part of economics. It may not be what most economists do, but it is extremely important too. Let us now get much more specific.

3. Cutting a cake

Imagine that there are two children, Alice and Bob. You have a cake and want to divide it between the two children. Your goal is to divide it so that each child is happy with his or her portion. So this means that Bob should

CONTACT Eric Maskin emaskin@fas.harvard.edu Director, Maskin Research Center of China's Economic Development, Zhejiang University, Hangzhou, PR China
†For this article-related contact, please send inquiries to tncr.special@gmail.com (attn.: Jen)

*Adams University Professor, Department of Economics, Harvard University, Cambridge, MA, USA.

think that he has at least half of the cake, and Alice should think that she also has at least half. This may not sound like the most important problem in the world. However, in a family, it can be critical.

We will say that, if the cake is divided so that each child is happy with his or her piece, we have a fair division. How do you achieve such a fair division? If you know that the children see the cake the same way that you do, there is a simple solution: you just take a knife and cut the cake in half, and give each child one of the pieces. Because we are assuming that they see the cake the same way you do, Alice and Bob will each think that they have half the cake and that is the end of the story. The problem is that, in real life, children almost never see things the same way that an adult does. You might think that you have divided the cake equally, but Bob might think that Alice's piece is bigger. So, here is the problem: you want to achieve a fair division, but you do not actually have enough information to do so because you do not know how the children see the cake. The mechanism design question is this: is there a mechanism or procedure that you can follow that will result in a fair division even though you do not have enough information to say what a fair division is yourself?

This problem is actually very old. It is literally thousands of years old. It is even mentioned in the Old Testament of the western Bible. Specifically, there is a passage where Lot and Abraham want to divide some grazing land between them in a fair way. But dividing grazing land is the same problem as dividing a cake. And just as the Old Testament states the problem, it also provides a solution.

As you will see, the solution is extremely simple but clever. This is a feature of mechanism design quite generally. Solutions tend to be ingenious, but they are so simply ingenious and you wonder after you see why you did not think of this before. That is because these mechanisms are so clever.

So here is the solution for the cake problem. What you should do is to have one of the children, say, Bob cut the cake. Then have the other child, Alice, choose the piece she prefers.

This is called the divide-and-choose mechanism. Why does it work? Well, when Bob cuts the cake, he has a strong incentive to make sure that each piece is the same size from his point of view. Why? Because if one piece is bigger, he knows Alice will take it, and he will be left with the smaller piece. So when he is cutting the cake, he will ensure that whichever piece Alice takes, he is happy with the other. This means Bob will be happy. And Alice will be happy because she can choose her favourite piece. Thus, the divide-and-choose mechanism solves the problem. Of course, it is a simple problem. Nevertheless, it is already complicated enough to illustrate some of the main features of mechanism design.

Specifically, in mechanism design, the mechanism designer himself does not know in advance what outcomes are optimal. In the cake problem, you want to divide the cake fairly, but you do not know what a fair division is because you do not know how the children view the cake. That means you have to proceed indirectly through a mechanism. But there is an additional problem, which is that the participants in the mechanism do not share your goals. The goal in the cake problem is to achieve a fair division, but Alice and Bob do not care about a fair division; they each just want as much cake as possible. They have their own objectives, and the mechanism has to be compatible with those objectives. In other words, it has to be what we call incentive compatible.

4. Allocating radio spectrum

Let us move to a somewhat more complicated example, one that has been critically important to the modern world: the problem of allocating radio spectrum to telecom companies. About 20 years ago, many telecom companies came into existence. Countries around the world realised that it no longer made sense for governments to monopolise the radio broadcasting spectrum. So many governments decided to transfer large parts of the radio spectrum from the public sector to the private sector. These transfers made the information and communication revolution possible. They made mobile phones, satellite TV, and all the other modern miracles we take for granted reality. Let us look at a simple example of transferring radio frequencies from the public to the private sector.

Imagine that there is a government who wants to transfer the right to use a particular band of radio frequencies to one of several telecom companies interested in these frequencies. We call the right to use these frequencies a licence. And let us suppose that the goal of the government is to put the licence into the hands of the company that values it the most. In other words, the government wants an efficient outcome (Economists say that resources are allocated efficiently if the companies who control them are the ones getting the most value out of those resources). So how does the government achieve an efficient outcome? Assume that the government does not know how much each company values the licence. Then how can it know which company has the highest value?

The simplest mechanism would be for the government to ask each company how much it values the licence and to award the licence to the one claiming to have the highest value. But you can see that this mechanism is not going to work very well because each company will realise that it has a better chance of getting the licence when it exaggerates its value. So all the companies will exaggerate, and the government will have no idea which one really values it the most. So it needs to try something a bit more sophisticated.

The government could instead have each company make a bid for the licence. A bid is a statement about how much the company is willing to pay for the licence. The government could then award the licence to the company making the highest bid and have the winner pays its bid.

This alternative mechanism is better than the first one because now companies would not exaggerate anymore. If the licence is worth $10 million to my company, I am not going to bid $12 million, because if I did bid $12 million and won, I would have to pay $12 million, and that is too much. So, companies would not exaggerate. But this mechanism will fail because of the opposite problem: companies now have an incentive to understate the value of the licence. Why? Let us imagine that the licence is worth $10 million to my company. If I bid $10 million and I won, I would be getting something worth $10 million, but I had to pay $10 million. So my net benefit would be zero. I might as well have stayed home and not bothered. So I am not going to bid $10 million. I will bid something less, maybe $8 million. That will reduce my chance of winning. But if I do win, I will get a profit. So now all companies will be underbidding, and once again, there is no guarantee that the company that values it the most will actually win.

At this point, you may be wondering if there is any mechanism that gets things right. In the first mechanism, companies exaggerate. In the second one, companies understate. Is there a mechanism that gives bidders the incentive to bid exactly what the licence is worth to them?

Well, it turns out that the answer to that question is yes. But this was not discovered thousands of years ago. In fact, the discovery was made only about sixty years ago by the American economist William Vickrey. Once again, you will see that the solution is very simple, but very clever. Specifically, Vickrey proposes that every company should make a bid for the licence. As before, the winner is the highest bidder. But now, instead of paying its own bid, the winner pays the second highest bid. So this is sometimes called the second-bid mechanism.

Here is an example. If there are three bidders and one bids $10 million, one bids $8 million, and one bids $5 million, the winner will be $10 million bidder because that is the highest bid, but it will pay only $8 million, because that is the second highest.

Now I claim that in this second-bid mechanism, companies will bid exactly what the licence is worth to them. They neither exaggerate nor understate. First, they would not understate because a company now does not pay what it bids anyway, it pays the second highest bid. So if the licence is worth $10 million to me and I bid $9 million, I do not pay $9 million if I win; I pay $8 million if that is the second highest bid. Reducing my bid to $9 million does not reduce my payment. In fact, reducing my bid might lose me the licence altogether. For example, if I bid $7 million, I will lose to a company that bids $8 million. But If I bid $10 million, I would have won with a nice two million dollar profit, 10 million minus 8 million. So companies never gain from underbidding in the second bid mechanism. And they might do very badly by underbidding. So they are not going to underbid. But they are also not going to overbid. Let us continue to suppose that the licence worth $10 million to me, but I exaggerate and bid $12 million. Could that ever be good for me? Well, if I bid $12 million and someone else has bid $11 million, I will win. But I will have to pay $11 million. And that is too much. So if I overstate, then I run the risk of paying more than the licence is worth to me. So I will bid exactly $10 million, exactly what the licence is worth to me. But if all companies bid what the licence is worth to them, then the highest bidder will indeed be the company with the highest value. And so the problem is solved.

5. Mechanism design for energy

Let us look at one more example. This will be slightly more complicated than the previous ones. It is an energy example. Imagine a society in which consumers need energy. To make matters simple, suppose that there are just two consumers. We will call them Alice and Bob again. Let us suppose that there is also an energy authority and its job is to decide what kind of energy Alice and Bob are going to have. There are four possibilities. There is natural gas. There is oil. There is nuclear power, and there is coal. The energy authority has to choose one of those (it is too expensive to have more than one kind of energy). Now, which one should it choose? Well, presumably, the authority wants to choose an energy source that Alice and Bob like; the authority wants to satisfy their preferences. But the problem is that the authority does not know what Alice and Bob want. Assume that there are two possibilities for what Alice and Bob want. We will call them two states of the world. In state 1, Alice and Bob do not care very much about future consumption. They care mainly about current consumption. In state 2, Alice and Bob put a lot of weight on the future, not so much on the present.

Suppose that Alice cares mostly about how convenient the energy source is. In state 1 (that is the case where she cares mostly about current consumption), she likes gas the most, because gas is the easiest to use. Then she likes oil, coal, and nuclear power in that order. Nuclear power is last on the list because it is inconvenient to use. For instance, driving a car with nuclear power will be quite complicated. But in state 2 (where she is putting most of the weight on the future) nuclear power rises to the top because she expects that there will be technological improvements that make nuclear power much easier to use. After nuclear power, her preference is for gas, coal, and oil in that order. Now, what about Bob? Suppose that Bob cares mostly about how safe the energy source is. So in state 1, he likes nuclear power the most because it is the safest. Then come oil and coal, and gas is at the bottom because he is worried about gas explosions. But if he puts more weight on the future, now nuclear power goes to the bottom because he is worried about the long-term problem of getting rid of nuclear waste. So his ranking is oil, gas, coal, and then nuclear power. We summarise Alice's and Bob's preferences in the following table.

State 1		State 2	
Alice	Bob	Alice	Bob
gas	nuclear	nuclear	oil
oil	oil	gas	gas
coal	coal	coal	coal
nuclear	gas	oil	nuclear

5.1. The energy authority's goals

What should the energy authority do given that Alice and Bob's preferences are different? We would argue that oil makes a good compromise in state 1. Nuclear power is not a good compromise, because although Bob likes nuclear power, Alice does not like it all. And Alice likes gas, but Bob does not like gas at all. So nuclear power and gas are not good compromises. And also coal is a not good compromise because both Alice and Bob prefer oil to coal, so oil really makes the best compromise in state 1. And similarly, gas makes a good compromise in state 2. Nuclear power and oil do not make good compromises, because Alice hates oil and Bob hates nuclear power. Coal, once again, is not a good compromise because both Alice and Bob prefer gas to coal. So if the energy authority knew what the state was, it would choose oil in state 1 and gas in state 2.

Table on energy consuming		
	Bob	
Alice	Oil	Coal
	Nuclear	Gas

5.2. Energy mechanisms

The problem is that the authority does not know what state it is. So what can it do? Well, the authority could ask Alice and Bob what the state is. But the difficulty is that that is not likely to work very well. You see, Alice is always going to say that state 2 is the state even in state 1, because Alice always prefers gas to oil. She wants to make the authority think that state 2 is the actual state, so that it will choose gas. Bob has just the opposite incentive. Bob prefers oil to gas in both states. So he wants to make the authority think that state 1 is the actual state, so that the authority will choose oil. So he is always going to say state 1. Alice will say state 2. And the poor energy authority will have no idea of the actual state.

So simply asking consumers about their preferences is not going to work. The authority is going to have to do something more sophisticated. What the authority can do is to have Alice and Bob play the mechanism illustrated on the right. If you have seen some game theory, you might recognise this table as a game in which Alice chooses rows as strategies (Alice can choose the top row or bottom row), and Bob chooses columns as strategies (Bob can choose the left column or the right column). Then the outcome of the game is simply the intersection of Alice and Bob choices. So if Alice chooses the bottom row and Bob chooses the right column, the outcome is gas. This simple mechanism will lead to the right outcome.

Imagine that state 1 is the actual state. What will happen if Alice and Bob play this game in state 1? If Alice predicts that Bob is going to play the left column, Alice is going to play the top row, since if she plays the top row, she gets oil, and if she plays the bottom row, she gets nuclear power. And notice that Alice prefers oil to nuclear power in state 1. But in fact, Bob will want to play the left column, because regardless of what Alice does, Bob is always better off playing the left column. If he plays the left column and Alice chooses the top row, Bob gets oil rather than coal and Bob prefers oil to coal. If Alice chooses the bottom row and Bob goes left, he gets nuclear power rather than gas, but he prefers nuclear power to gas.

And so we have a strong prediction in this game: in state 1, Alice will choose the top row, and Bob will choose the left column. This is what game theory calls a Nash equilibrium, after John Nash, the hero of the movie, A Beautiful Mind. One of Nash's great discoveries was how to predict the outcome of a game like this. In state 1 the prediction is that: Bob will choose the left column, and Alice will choose the top row. And that will lead to oil, which is exactly the right outcome, according to the energy authority.

So this game works successfully in state 1. It also works in state 2. We would not go through the details because they are very similar to those in state 1. But you can easily work out that Alice is going to play the bottom row and Bob is going to play the right column. Thus, the mechanism leads to gas, and gas is the right outcome in state 2. So this simple mechanism implements the energy authority's goals. It solves the problem.

6. More general results

We have shown you three examples: the cake, the telecom, and the energy examples. In all three cases, we showed you a mechanism that solves the problem.

Now you might say, well, that is a little bit unsatisfying, because we did not tell you how we found these mechanisms. We just showed them to you. It is like a magic trick. We pulled a rabbit out of a hat. We did not tell you how we did that trick. You might want to go deeper and understand how we found such mechanisms. In fact, you might ask how we even knew that there were solutions to the problems. So the general questions to ask in mechanism design are; first, how can we tell whether a goal can be implemented or not? And, if it is implementable, how can we find a mechanism that implements it? Those were the questions that 'Nash Equilibrium and Welfare Optimality' (see Maskin 1999) answered many years ago. We are not going to go into the details of the paper here because it is too technical. But if you are interested in reading more about mechanism design, you might look at it. It is not terribly difficult to read.

7. Concluding remarks

We have looked at three possible applications of mechanism design, but there are literally thousands of others. Over the last 60 years economists have examined many of these.

Let us just mention one important application that has not been completely worked out. This is how to solve the problem of climate change. We all know that the earth's climate is getting warmer. And we all know why that is happening: We humans are responsible for putting greenhouse gases like carbon dioxide into the atmosphere. The obvious solution to the problem is to stop emitting so much greenhouse gas. But the problem is that this goal puts the different countries of the world into conflict with each other. Each country would be happy if other countries made reductions. But it does not want to make reductions itself. Why not? Because making reductions is expensive. It means getting rid of old technology, adopting carbon-free technology, and imposing carbon taxes on companies and citizens. All of that is costly for the economy.

For example, China would be happy if other countries reduced emissions but would prefer not to reduce itself. How do we solve that problem? We can solve it by designing an international treaty for greenhouse gases, which brings down emissions to a safe level and also gives every country the incentive to actually sign the treaty.

If you think about it, an international treaty is simply a mechanism for reducing carbon emissions. Have we designed a successful international treaty for carbon emissions? Not yet. But I am confident that we will solve that problem. And when we do, mechanism design will be at the centre. Mechanism design will be the method by which the problem is solved.

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Notes on contributor

Eric Maskin is the Director of the Maskin Research Center of China's Economic Development at Zhejiang University, Hangzhou, PRC and the Adams University Professor at Harvard. He has made contributions to game theory, contract theory, social choice theory, political economy, and other areas of economics. He received his A.B. and Ph.D from Harvard and was a postdoctoral fellow at Jesus College, Cambridge University. He was a faculty member at MIT from 1977-1984, Harvard from 1985-2000, and the Institute for Advanced Study from 2000-2011. He rejoined the Harvard faculty in 2012. In 2007, he was awarded the Nobel Memorial Prize in Economics (with L. Hurwicz and R. Myerson) for laying the foundations of mechanism design theory.

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