Policy and Decision Models
Final Examination
29 January 2009

Topic: Copenhagen Climate Conference

Instructions

The following exam consists of 15 questions, for a sum total of 100 points. The questions all discuss implications of the recent Copenhagen climate conference. There is no one single text for the case; instead there is a running discussion throughout.

The questions are selected and ordered as appropriate for the case. They are not, for instance, ordered according to the presentation in Straffin. Some questions are analytical while others are interpretative. If asked your opinion, what is expected is a clear and defensible answer. In fact, for these interpretive questions there may be multiple possible answers. Note that some questions are worth 10 points, while others are worth 5 points.

You have three hours; collect your points wisely. You will be given three warnings as the exam completes. The exam is open book. You may use a calculator. Please write your answers with the paper provided. Please include your name and student number on every sheet.

Question 1 (5 points). Carbon Apportionment

Table 1 below shows some comparative world statistics for Europe, U.S., China, and the rest of the world. Suppose the industrial era was just about to begin, and we knew that carbon dioxide was a "bad" which was to be apportioned carefully among the world's citizens. Select the metric of your choice for apportioning carbon, and defend your choice.

		GDP		Population		Person-Years
		billions 2010 USD$		millions		billion people-years
		2000	2050	2000	2050	1750-2050
Units	Rest of the World	24694	150005	4115	7366	574600
	Europe	10855	45425	386	471	74675
	US	12468	63426	272	420	37150
	China	7138	47783	1240	1437	187000
	Total	55155	306639	6013	9694	873425
Percent	Rest of the World	44.8%	48.9%	68.4%	76.0%	65.8%
	Europe	19.7%	14.8%	6.4%	4.9%	8.5%
	US	22.6%	20.7%	4.5%	4.3%	4.3%
	China	12.9%	15.6%	20.6%	14.8%	21.4%
	Total	100.0%	100.0%	100.0%	100.0%	100.0%

Table 1: Comparative World Statistics

	Delta GDP	Population	Geo Average	Percent Awarded	Percent Consumed	Difference
Rest of the World	125,311	7,366	30,382	65%	65%	0%
Europe	34,570	471	4,035	9%	11%	-2%
U.S.	50,958	420	4,626	10%	19%	-9%
China	40,645	1,437	7,642	16%	6%	11%
Total	251,484	9,694	46,685	100%	100%	0

Table A: Comparative World Statistics

When answering this question it is useful to make a distinction between "prescription," which is what would I recommend based on first principles, and "normative analysis" which is what am I capable of actually implementing. It may be hard to actually implement any prescriptive recommendation now, at the close of the carbon era. Most game theory analyses focus on "normative" or "strategic" analyses, which are not the games we should be playing, but the games we actually could be playing. However this question is more an EPA question and not a game theory question. I'm looking for prescriptions.

I would consider population to be the best index for allocating carbon. Having a clean and safe natural environment is a "right" which is to be shared among world citizens. You could either use world population in 2050, or you could consider the total number of people who have lived since the industrial revolution. These figures provide equivalent results. An alternative perspective is that economic development is a "right" and we should award carbon to those who need it to further develop. One submission examined the differences between GDP today and GDP in 2050 as an indicator of industrialization. I think it is hard to argue that carbon allocation should be according to GDP. This is tantamount to arguing that those citizens in the world who are currently wealthy inherently deserve to be wealthy.

The table above provides a geometric average of the two alternative perspectives. Regardless of which perspective you adopt, its clear that the U.S. has consumed more than its fair perspective of carbon, and China far too little. Ten percent of all anthropomorphic carbon is a lot of carbon -- 50 billion metric tons. If this is our prescription, then China should be allowed to burn freely at current rates for the next twenty years (see table 3 below)! Or, they should be renumerated for stopping the pollution.

Question 2 (5 points). Carbon Balances

The table below shows the actual total consumption of CO_2 by nation as of 2010. Of the total 511 billion tons which some say we can safely introduced into the atmosphere, we have used all but 26. We have, perhaps unknowingly, used almost the entirety of the permissible store of carbon dioxide in the atmosphere. Using your answer from question 1, and the summary values below, conclude which nations have spent too much, and which nations have spent too little.

	CO_2 Consumption to Date	
	Billion metric tons of CO2	Percentage
Rest of the World	315	64.9%
Europe	51	10.5%
U.S.	91	18.8%
China	28	5.8%
Total	485	100.0%

Table 2: Actual World Consumption CO_2 to Date

See the discussion above.

Question 3 (5 points). Calculating the Status Quo

The 2009 Copenhagen Climate Conference faced the following apparent status quo. The calculation involves calculating the costs of disastrous climate change (356 trillion USD), which in the table below is distributed according to world population. There are also benefits, which involve the potential unconstrained usage of carbon at today's rates. The table below shows that the status quo is most beneficial for the United States, which has a comparatively high usage, and a relatively low fraction of the world population. On the contrary, the rest of the world despite its high carbon usage cannot overcome the expected high burden of damage.

	Costs		Benefits		net
	percent population	Damages (trillion USD)	yearly carbon consumption (billion metric tons)	market value of continued consumption (trillion USD)	trillion 2010 USD
Rest of the World	76.0%	-270.56	6.16	7.55	-263.01
Europe	4.9%	-17.44	0.74	0.91	-16.54
U.S.	4.3%	-15.31	1.18	1.44	-13.87
China	14.8%	-52.69	2.52	3.09	-49.60

Table 3: The Status Quo

The calculated status quo is predicated on many assumptions. One is the discount rate for future generations. These calculations use 4% which assumes we only consider the next 25 years of cost. Another is the value per metric ton of carbon. These figures use a price of $49 metric tons, which is higher than current European market price ($18). Yet another is the distribution of damages. These figures distribute damage according to the proportion of world population. Arguably the rest of the world will have higher costs than shown here, since it lacks the wealth to mitigate the worst effects of change. A final assumption involves the total costs of disastrous climate change. The Stern Report places the costs at 4.5% of the world economy, while acknowledging that the true costs may be four times higher or lower.

In your opinion how robust are these estimates of the status quo? Which assumptions critically underpin these estimates? Defend your answer.

The best answers here recognized that I was asking you to prioritize those elements of the model which need extra support or validation. Bringing in ideas from your courses or lectures on Uncertainty was welcome. Restating the assumptions was ok; identifying those assumptions which you find most troublesome is even better.

I find the cost of damage assumptions to be the most troubling, as well as the likely incidence of damage. While I do think more damages will be concentrated in the "rest of the world" I suspect that the developing world will bear an even higher cost than suggested here. These nations do not have the resources to dedicate to climate change adaptation. I suspect that we could do some exploratory modeling here, since these results could affect the status quo. Nonetheless, I hypothesize that this simplified model would hold up well under a range of planning assumption.

The discount rates are also troubling, but I fear we may have to accept them for the lack of something better. We could reproduce the model with multiple discount rates, but the fundamental discomfort with discount rates would remain. A more satisfactory, but more difficult, model would be a generational model of strategic bargaining, or perhaps a staged model of cooperation.

Note that there are a few existing game theory models of climate change negotiation. At last count, I found four articles on the topic. It is a new application of study!

Question 4 (10 points). N-Person Games of Remediation

For the following question assume that the rest of the world continues to pollute. The players in the game are Europe, U.S. and China. Each player has two strategic options -- continue to pollute, or to remediate. Remediation involves paying the market value of carbon consumed by the polluting players. If multiple players remediate, they share the costs of remediation equally. If all players remediate then they divide the value of the remaining carbon equally. If no player remediates then climate change occurs, and the status quo payoffs given above apply.

The strategic form of the three person game based upon these assumptions is as follows. Draw the movement diagram associated with this game. Identify and interpret any pure strategy Nash equilibria you may have found.

China P

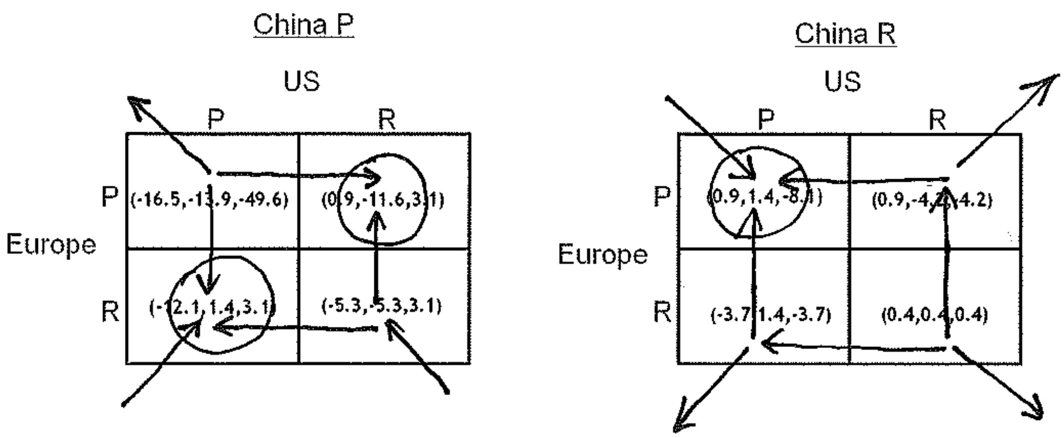
Europe \ US	P	R
P	(-16.5,-13.9,-49.6)	(0.9,-11.6,3.1)
R	(-12.1,1.4,3.1)	(-5.3,-5.3,3.1)

China R

Europe \ US	P	R
P	(0.9,1.4,-8.1)	(0.9,-4.2,-4.2)
R	(-3.7,1.4,-3.7)	(0.4,0.4,0.4)

Figure 1: Three-Person Game of Carbon Remediation. Payoffs in trillion USD to (Europe, US, China).

There are three equilibria here. One of each of the players remediates (cleans-up) and the other two pollute. See the movement diagram below. It is helpful to circle the equilibria.



Question 5 (5 points). Climate Change as the Prisoner's Dilemma

Is the game presented above an N-Person Prisoner's dilemma? Or is it another dilemma such as Chicken?

It is not an n-person prisoner's dilemma. In the prisoner's dilemma, all players would prefer to pollute if the other players pollute, even though it makes them worse off. It is however a dilemma of another kind -- the Chicken dilemma.

Question 6 (10 points). Chinese Strategic Moves

In the real world China is attempting to force Europe and the United States to move first in the game by having them commit to carbon abatement. Use the N-person game presented above, and Schelling's concept of strategic moves, to evaluate whether this is an effective strategy for China. Can you suggest other strategic moves which might work better?

In the chicken dilemma you want to be the one to move first on the actions you desire. Basically, China needs to convince the U.S. and Europe that it will consume a fair share of carbon. So China ought to be convincingly and compellingly committing to pollution! In this case, being the first to pollute is being the last to commit to pollution reduction. However the claim that China will pollute at all costs is just not credible.

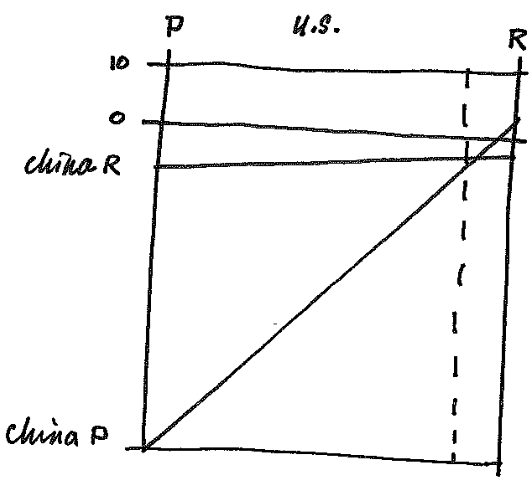
I received nice arguments that a coupled threat and promise would be a good strategic move for China. China threatens to pollute if other nations do not clean-up, but promise to clean-up if they do.

Question 7 (10 points). Mixed Strategies

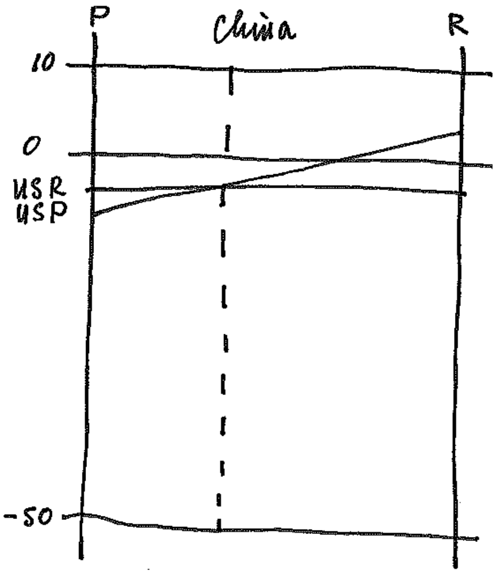
Suppose Europe was committed to a strategy of pollution. Simplify the game above for the players U.S. and China. Is a mixed strategy solution possible?

		China P		China R	
U.S. π	P	-13.9	-49.6	1.4	-8.1
U.S. $1-\pi$	R	-11.6	3.1	-4.2	-4.2

There is a mixed strategy here. You can see the strategy easily in the mixture diagram presented below.



The associated mixed strategy requires that the U.S. remediates a lot, and China remediates a little.



I received various incorrect argumentations that there was no strategy. The arguments were based on zero-sum games. This game is non-constant sum, and therefore these arguments do not apply. The underlying algebra of the strategy is worked out below using the pay-off equalizing method.

Let π equal U.S pollution strategy. By the pay-off equalizing strategy

$$-49.6\pi + 3.1 - 3.1\pi = -8.1\pi - 4.2\cancel{\pi} + 4.2\pi$$
$$3.1 - 3.1\pi = (49.6 - 8.1)\pi - 4.2 + 4.2\pi$$
$$7.3 - 3.1\pi = 41.5\pi - 4.2 + 4.2\pi$$
$$7.3 + 4.2 = 41.5\pi + 4.2\pi$$
$$11.5 = 45.7\pi$$
$$\frac{11.5}{45.7} = \pi = 25\%$$

The U.S should partially remediate. Let ρ equal China pollution strategy

$$-13.9\rho + 1.4 - 1.4\rho = -11.6\rho - 4.2 + 4.2\rho$$
$$1.4 - 1.4\rho = (13.9 - 11.6)\rho - 4.2 + 4.2\rho$$
$$1.4 - 1.4\rho = 2.3\rho - 4.2 + 4.2\rho$$
$$5.6 - 1.4\rho = 6.5\rho$$
$$5.6 = 7.9\rho$$
$$\frac{5.6}{7.9} = \rho = 71\%$$

China should mostly pollute.

The value of the game is not required. If you do investigate the value of the game you will find that the outcome is also a Nash equilibrium for Europe The resultant pay-offs for Europe show that Europe's strategy of polluting is in fact a Nash equilibrium strategy. A mixed strategy where the U.S. commits to pollution is also possible. A mixed strategy is not possible if China commits to pollution.

Question 8 (5 points). Climate Change and Institutional Arrangements

Were all the outcomes achieved in the n-person game discussed above Pareto optimal? Is there any apparent need for cooperation or arbitration? Is complete carbon abatement for all parties actually Pareto optimal?

No, the outcomes are not Pareto optimal. Europe is better off if China or Europe remediates. U.S. is better off if China remediates. China is best off if Europe and U.S. remediate. No one wants the failed coordination implied by the mixed strategies discussed above. The best possible situation would be if China could be induced to clean up, and the associated costs were distributed. At stake is roughly 11 trillion dollars! Mediation is needed.

Its tempting to say that climate change agreements would restore Pareto optimality, but they will not. Obviously nations are made worse off by being forced to abate their carbon consumption!

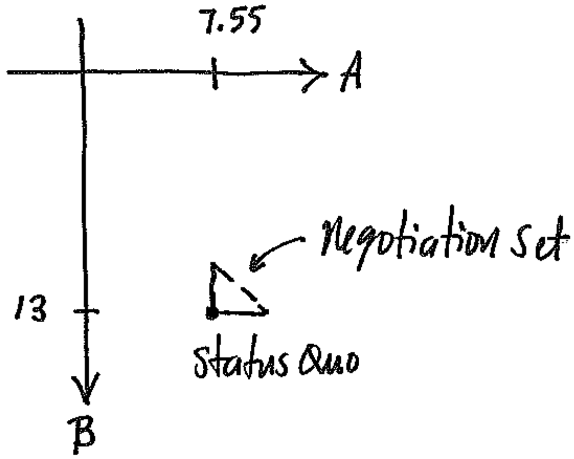
Question 9 (5 points). Arbitration for Sustainable Development

In this question you are asked to help arbitrate aid payments to the “rest of the world” to encourage sustainable development, and to abate the worst effects of climate change. Let player A be the "rest of the world," and player B is "Europe, U.S. and China."

Our analysis of the N-player setting above assures us that at least one of the major players will abate the worst effects of climate change. Therefore set the status quo to be 7.55 for player A, and -13.00 for player B. This reflects unabated consumption on the part of the rest of the world, while Europe, U.S. and China presumably pays for its amelioration. The Pareto optimal outcome would be to agree to divide the remaining 26 billion tons of carbon and to spend no further carbon. The pool of carbon remaining provides an industrial market value of 1.3 trillion USD. Assume all distribution of costs and benefits is possible, although you should not permit either party to be made worse off by the negotiation.

Draw the pay-off polygon.

The pay-off polygon is shown below. The three corner points are the status quo, player A consumes all the carbon, and player B consumes all the carbon. The drawing is not to scale.



Note that we can speak of Pareto optimality here only because the U.S., Europe and China have been grouped as a single actor. Note that 13 billion is the total costs of remediation, and 7.55 billion are the economic benefits of carbon consumption to the rest of the world.

Question 10 (10 points). Nash Arbitration of Climate Change

Using the information provided from the previous question, use the Nash arbitration to calculate a fair payoff to the two players. What do these results suggest about the possibility of linking aid to low carbon development? Would the required value per metric ton of carbon need to be higher or lower than the assumed $49 rate?

The formulation and optimization of the Nash arbitration solution is given below.

Let x be the share of carbon awarded to player B
The nash arbitration quantity is

$$U = (-13-x)(7.55-1.3+x)$$
$$U = (-13-x)(6.25+x)$$
$$0 \le x \le 1.3$$

Maximize U subject to the constraint.

$$U = -81.25 - 6.25x - 13x - x^2$$
$$U = -81.25 - 19.25x - x^2$$
$$\frac{dU}{dx} = -19.25 - 2x = 0$$
$$x = -19.25/2 = -9.625$$

This solution shows that the arbitration point lies out of the constraint boundaries. Player B "U.S., Europe and China" can claim none of the remaining carbon, and must give it all to the rest of the world. Alternatively, they can purchase it back at an agreed upon price.

The fact that Player B can claim none of the remaining carbon (unless they purchase it from player A) suggests that the carbon price has been set too low. Consider the following implementation arguments.

If we interpret the Nash arbitration solution, Player B is "selling" carbon permits for 26 billion metric tons of carbon plus the 154 billion metric tons (25*6.16) that the developing world is expected to consume in the next 25 years. These permits are set at a total value of 8.85 trillion dollars (7.55 +1.3) in cross payments. The new value of carbon permits is about $53 dollars per metric ton.

Question 11 (5 points). Cooperative Games and Framework Negotiations

The previous questions demonstrate that climate change operates within a multi-actor setting. New institutional arrangements are needed for the benefit of all. Cooperative games attempt to model the effects of multi-actor negotiations and bargaining. Which concept from Straffin do you think best models the actual dynamics of the climate change conference? Why do you think so?

I like the normative aspects of the Shapley value as a "fair" and achievable outcome given process considerations. The Gately point would also be an interesting measure to prevent disruption by the world's big polluters (U.S. and China).

Question 12 (5 points). Characteristic Function of Climate Change Cooperation

For the next several questions we use a short-hand to consider the four players discussed above. Let the "rest of the world" be player A, let Europe be player B, let the United States be player C, and let China be player D.

Assume that all coalitions face the lesser of two costs: abating the pollution of others, or facing the costs of climate change. All of the one player coalitions can secure the benefits of continued consumption, and all coalitions consisting of two or greater players can share the economic benefits of sustainable carbon emissions. The resulting game in characteristic function is shown below. Note that these figures are in trillions of US $ (rounded).

v{ϕ}=0

v{A}=2 v{B}=-11 v{C}=-10 v{D}=-7

v{A,B}=-3 v{A,C}=-3 v{A,D}=-1 v{B,C}=-9 v{B,D}=-8 v{C,D}=-7

v{B,C,D}=6 v{A,C,D}=0 v{A,B,D}=0 v{A,B,C}=-2

v{A,B,C,D}=1

Figure 2: Characteristic Function of Climate Negotiations Game

Is the game constant sum? Is the game super-additive? Find the strategic equivalent of this game.

The game is clearly not zero sum. If it were, then the value of ABCD (1) should be equal to the value of ABC (-2) plus D (-7). It does not, hence the game is not zero sum.

You can see this for instance with adding the value of A and B (2-11=-9). This is definitely not the value to AB (-3).

Its harder to show that the game is not constant sum. We must show that there is no value that we can add to each player when joining a coalition so that all the coalitions are of constant sum.

#1	$B + C = 12$
#2	$A + B = 6$
#3	$A + C = 5$
#4	$2A + B + C = 11$
#5	$2A = -1$
#6	$A = -1/2$
#7	$B = +5.5$
#8	$C = +4.5$
#9	$B + C = 10$

Our argument is based on proof by contradiction. Let the quantities A, B, C and D be a quantity we add to all coalitions involving these players. Assume that there is a constant sum we can add to all coalitions containing A. Likewise assume there are different sums we can add to B or C. Given the value of the one and two player coalitions the equalities 1 to 3 above must old. Adding 1 to 3 gives us equation 4. Equation 4 minus equation 1 shows that A must be equal to -1/2. This is shown in equations 5 and 6. If this is true than the quantity added to B must be 5.5 (equation 7), and the quantity added to C must be 4.5 (equation 8). The sum of B and C must therefore be 10. But this contradicts equation 12. Therefore there is no possible additive sum.

The game is not superadditive. Consider the case v(A,B,C,D) and the disjoint coalitions v(A) and v(B,C,D). The whole (1) is less than the sum (8) of the parts! This shows there is little incentive for the rest of the world to join in a coalition with the developed nations of China, U.S. and Europe.

The calculations needed to find the strategic equivalent are shown below. First we "zero out" the payments to the single coalitions. Then we divide through by the payment to the supercoalition.

$v\{\phi\} = 0$	0	0
$v\{A\} = 2 - 2$	0	0
$v\{B\} = -11+11$	0	0
$v\{C\} = -10+10$	0	0
$v\{D\} = -7+7$	0	0
$v\{A,B\} = -3-2+11$	6	6/27
$v\{A,C\} = -3-2+10$	5	5/27
$v\{A,D\} = -1-2+7$	4	4/27
$v\{B,C\} = -9+11+10$	12	12/27
$v\{B,D\} = -8+11+7$	10	10/27
$v\{C,D\} = -7+10+7$	10	10/27
$v\{B,C,D\} = 6+11+10+7$	34	34/27
$v\{A,C,D\} = 0+-2+10+7$	15	15/27
$v\{A,B,D\} = 0+-2+11+7$	16	16/27
$v\{A,B,C\} = -2-2+11+10$	21	21/27
$v\{A,B,C,D\} = 1-2+11+10+7$	27	27/27

The subadditive nature of the game becomes quite clear when shown in strategic form. The U.S., Europe and China pay quite a lot to bring the rest of the world into the coalition.

Question 13 (10 points). Shapley Value of Climate Negotiations

In this question we calculate the Shapley value of a game involving climate change negotiation. The Shapley value is a natural extension of Nash arbitration to a multi-actor setting. The Shapley value is arguably the most fair process available for mediating games which in themselves may not be very fair. The Shapley value does not claim that it can be easily adopted or implemented. Nonetheless in this problem it is helpful for setting appropriate expectations in the climate change negotiation process.

Find the Shapley Value for the game in characteristic function form as given in the previous question. Convert the figures into billions of tons of carbon. Interpret the results, and provide brief recommendations for implementation.

	A	B	C	D
ABCD	2	-5	1	3
ABDC	2	-5	1	3
ACBD	2	1	-5	3
ACDB	2	1	-5	3
ADBC	2	1	1	-3
ADCB	2	1	1	-3
BACD	8	-11	1	3
BADC	8	-11	1	3
BCAD	7	-11	2	3
BCDA	-5	-11	2	15
BDAC	8	-11	1	3
BDCA	-5	-11	14	3
CABD	7	3	-10	1
CADB	7	1	-10	3
CBAD	7	1	-10	3
CBDA	-5	1	-10	15
CDAB	7	1	-10	3
CDBA	-5	13	-10	3
DABC	6	1	1	-7
DACB	6	1	1	-7
DBAC	8	-1	1	-7
DBCA	-5	-1	14	-7
DCAB	7	1	0	-7
DCBA	-5	13	0	-7
ϕ	2.83	-1.58	-1.17	0.92
	Rest of World	Europe	United States	China

The game has the Europe and United States paying for abatement, and China and the rest of the world receiving payment or cross-transfers.

Shapley understands this process by considering those situations which show a high marginal cost or benefit. Europe, United States and China all pay a heavy process when they initiate a climate change coalition.

However the costs are higher, and the benefits are lower, when the United States and Europe play. China is thereby advantaged. The rest of the world only suffers in a cooperative arrangement when they are last tot

Question 14 (5 points). China's Bargaining Position

Consider the Shapley value for China, as calculated in the previous question. Explain why Shapley recommends this value for China. Shapley recommends a "fair value" for the game as played today. Is this value also normatively fair based on your previous conclusions in question 2?

The United States and Europe state that they expect China to make immediate commitment to reducing emissions in Copenhagen. Is this a reasonable request, at least according to Shapley?

Thus, China actually receives payment according to Shapley; the U.S. and Europe make cross-payments. It is not reasonable to expect China to make an immediate commitment either normatively or prescriptively.

Question 15 (5 points). Green Innovation

The climate change negotiations ended without any binding commitment for future change. Investors and green innovators were expressly disappointed with the outcomes. The following question provides a "story which could be true" regarding the link between climate negotiation and new innovation.

Some commentators suggest that green innovation could be a \$1.8 trillion dollar industry. While on the face of it this is a huge sum, when amortized on an annual basis this figure is less than 0.3% of the combined economy of U.S. and Europe.

Assume three players: governments, investors and inventors. Governments can commit, investors can invest, and inventors can invent. Investors can profit if the government commits; the long-term price of carbon is liable to increase from today's \$18 per metric tons to figures in the range of \$49 metric tons. Inventors profit only if they invent, are funded by investors, and there is government commitment for climate change. Governments must pay up to \$1500 billion if they commit to climate change treaties. On the other hand, they can also profit from collecting on a portion of the profits of investors and inventors in taxes. The game is shown below.

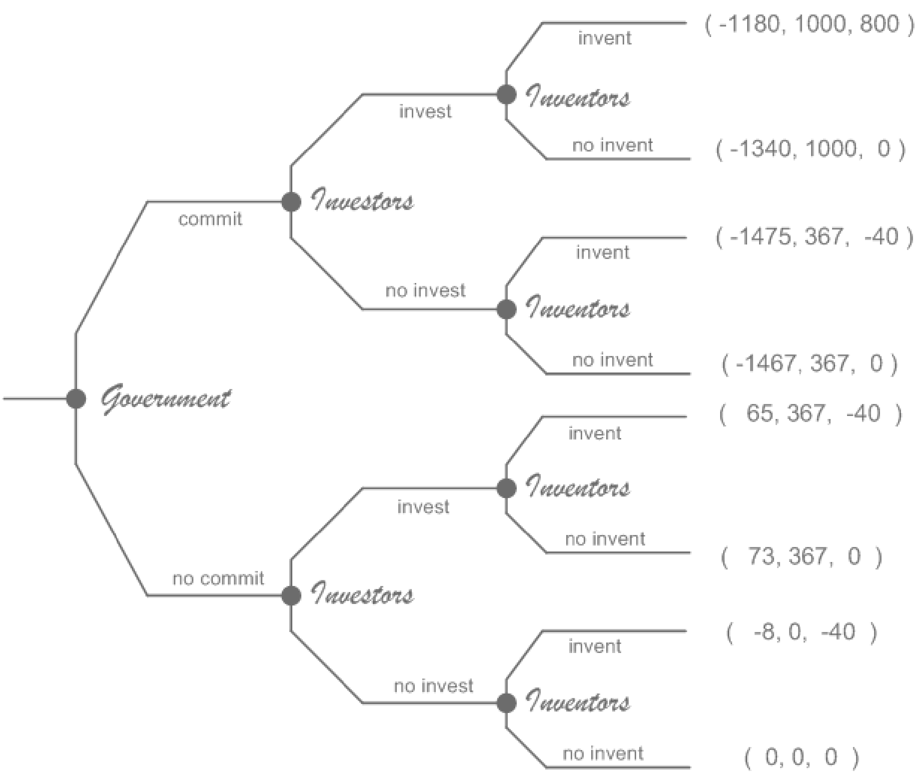
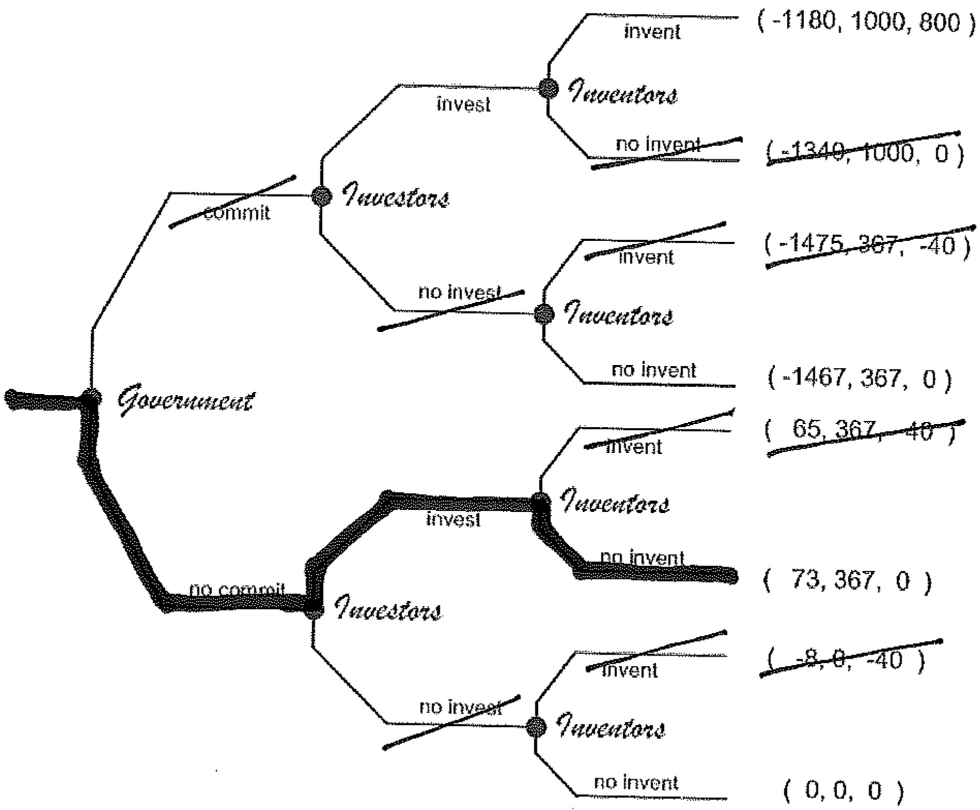


Figure 3: A Game of Green Innovation

Calculate the pure strategy equilibrium of this game.

This game is most easily solved in extensive form. Since there are no information sets (all moves and all payoffs are common knowledge), we can use backwards induction to solve the problem. Starting from the end of the tree, the inventors make their choices.



We compare the best decisions available to the inventors. They invent only if government commits, and investors commit. We can see this by examining the available pay-offs at the leaves of the tree. We cross off all other branches.

Inventors will always invest. Again, we compare the leaves of the tree to select the best strategies for the inventors. Thus, we cross off the "no invest" paths. Finally, government will either commit or not commit. The tree as given shows that there are currently fewer costs for "no commit" (73 versus -1180).

The resultant play is therefore "no commit, invest, no invent." There was a good discussion in a submitted exam about where to best intervene in the tree to achieve the Pareto optimal outcome "commit, invest, invent!"