7

Reaching Agreements

An obvious problem, related to the issue of cooperation, is that of *reaching agreements* in a society of self-interested agents. In the multiagent world that we all inhabit every day, we are regularly required to interact with other individuals with whom we may well not share common goals. In the most extreme scenario, as discussed in the preceding chapter, we may find ourselves in a zero-sum encounter. In such an encounter, the only way we can profit is at the expense of our opponents. In general, however, most scenarios in which we find ourselves are not so extreme - in most realistic scenarios, there is some potential for agents to reach *mutually beneficial agreement* on matters of common interest. The ability to reach agreements (without a third party dictating terms!) is a fundamental capability of intelligent autonomous agents - without this capability, we would surely find it impossible to function in society. The capabilities of *negotiation* and *argumentation* are central to the ability of an agent to reach agreement.

Negotiation scenarios do not occur in a vacuum: they will be governed by a particular *mechanism*, or *protocol*. The protocol defines the 'rules of encounter' between agents (Rosenschein and Zlotkin, 1994). It is possible to design protocols so that any particular negotiation history has certain desirable properties - this is *mechanism design*, and is discussed in more detail below.

A second issue is, given a particular protocol, how can a particular *strategy* be designed that individual agents can use while negotiating - an agent will aim to use a strategy that maximizes its own individual welfare. A key issue here is that, since we are interested in actually *building* agents that will be capable of negotiating on our behalf, it is not enough simply to have agents that get the best outcome *in theory* - they must be able to obtain the best outcome *in practice.*

In the remainder of this chapter, I will discuss the process of reaching agreements through negotiation and argumentation. I will start by considering the issue of mechanism design - broadly, what properties we might want a negotiation or argumentation protocol to have - and then go on to discuss auctions, negotiation protocols and strategies, and finally argumentation.

7.1 Mechanism Design

As noted above, *mechanism design* is the design of protocols for governing multi-agent interactions, such that these protocols have certain desirable properties. When we design 'conventional' communication protocols, we typically aim to design them so that (for example) they are provably free of deadlocks, livelocks, and so on (Holzmann, 1991). In multiagent systems, we are still concerned with such issues of course, but for negotiation protocols, the properties we would like to prove are slightly different. Possible properties include, for example (Sandholm, 1999, p. 204), the following.

Guaranteed success. A protocol guarantees success if it ensures that, eventually, agreement is certain to be reached.

Maximizing social welfare. Intuitively, a protocol maximizes social welfare if it ensures that any outcome maximizes the sum of the utilities of negotiation participants. If the utility of an outcome for an agent was simply defined in terms of the amount of money that agent received in the outcome, then a protocol that maximized social welfare would maximize the *total* amount of money 'paid out'.

Pareto efficiency. A negotiation outcome is said to be pareto efficient if there is no other outcome that will make at least one agent better off without making at least one other agent worse off. Intuitively, if a negotiation outcome is not pareto efficient, then there is another outcome that will make at least one agent happier while keeping everyone else at least as happy.

Individual rationality. A protocol is said to be individually rational if following the protocol - 'playing by the rules' - is in the best interests of negotiation participants. Individually rational protocols are essential because without them, there is no incentive for agents to engage in negotiations.

Stability. A protocol is *stable* if it provides all agents with an incentive to behave in a particular way. The best-known kind of stability is *Nash equilibrium,* as discussed in the preceding chapter.

Simplicity. A 'simple' protocol is one that makes the appropriate strategy for a negotiation participant 'obvious'. That is, a protocol is simple if using it, a participant can easily (tractably) determine the optimal strategy.

Distribution. A protocol should ideally be designed to ensure that there is no 'single point of failure' (such as a single arbitrator) and, ideally, so as to minimize communication between agents.

The fact that even quite simple negotiation protocols can be proven to have such desirable properties accounts in no small part for the success of game-theoretic techniques for negotiation (Kraus, 1997).

7.2 Auctions

Auctions used to be comparatively rare in everyday life; every now and then, one would hear of astronomical sums paid at auction for a painting by Monet or Van Gogh, but other than this, they did not enter the lives of the majority. The Internet and Web fundamentally changed this. The Web made it possible for auctions with a large, international audience to be carried out at very low cost. This in turn made it possible for goods to be put up for auction which hitherto would have been too uneconomical. Large businesses have sprung up around the idea of online auctions, with eBay being perhaps the best-known example (EBAY, 2001).

One of the reasons why online auctions have become so popular is that auctions are extremely simple interaction scenarios. This means that it is easy to automate auctions; this makes them a good first choice for consideration as a way for agents to reach agreements. Despite their simplicity, auctions present both a rich collection of problems for researchers, and a powerful tool that automated agents can use for allocating goods, tasks, and resources.

Abstractly, an auction takes place between an agent known as the *auctioneer* and a collection of agents known as the *bidders*. The goal of the auction is for the auctioneer to allocate the *good* to one of the bidders. In most settings - and certainly most traditional auction settings - the auctioneer desires to maximize the price at which the good is allocated, while bidders desire to minimize price. The auctioneer will attempt to achieve his desire through the design of an appropriate auction ~~mechanism - the~~ rules of encounter while bidders ~~attempt~~ to achieve their desires by using a strategy that will conform to the rules of encounter, but that will also deliver an optimal result.

There are several factors that can affect both the protocol and the strategy that agents use. The most important of these is whether the good for auction has a *private* or a *public/common* value. Consider an auction for a one dollar bill. How much is this dollar bill worth to you? Assuming it is a 'typical' dollar bill, then it should be worth exactly $1; if you paid $2 for it, you would be $1 worse off than you were. The same goes for anyone else involved in this auction. A typical dollar bill thus has a *common value:* it is worth exactly the same to all bidders in the auction. However, suppose you were a big fan of the Beatles, and the dollar bill happened to be the last dollar bill that John Lennon spent. Then it may well be that, for sentimental reasons, this dollar bill was worth considerably more to you - you might be willing to pay $100 for it. To a fan of the Rolling Stones, with no interest in or liking for the Beatles, however, the bill might not have the same value. Someone with no interest in the Beatles whatsoever might value the one dollar bill at exactly $1. In this case, the good for auction - the dollar bill - is said to have a *private value:* each agent values it differently.

A third type of valuation is *correlated value:* in such a setting, an agent's valuation of the good depends partly on private factors, and partly on other agent's valuation of it. An example might be where an agent was bidding for a painting that it liked, but wanted to keep open the option of later selling the painting. In this case, the amount you would be willing to pay would depend partly on how much you liked it, but also partly on how much you believed other agents might be willing to pay for it if you put it up for auction later.

Let us turn now to consider some of the dimensions along which auction protocols may vary. The first is that of *winner determination:* who gets the good that the bidders are bidding for. In the auctions with which we are most familiar, the answer to this question is probably self-evident: the agent that bids the most is allocated the good. Such protocols are known as *first-price* auctions. This is not the only possibility, however. A second possibility is to allocate the good to the agent that bid the highest, but this agent pays only the amount of the *second* highest bid. Such auctions are known as *second-price* auctions.

At first sight, it may seem bizarre that there are any settings in which a second-price auction is desirable, as this implies that the auctioneer does not get as much for the good as it could do. However, we shall see below that there are indeed some settings in which a second-price auction is desirable.

The second dimension along which auction protocols can vary is whether or not the bids made by the agents are known to each other. If every agent can see what every other agent is bidding (the terminology is that the bids are *common knowledge),* then the auction is said to be *open cry.* If the agents are not able to determine the bids made by other agents, then the auction is said to be a *sealed-bid* auction.

A third dimension is the mechanism by which bidding proceeds. The simplest possibility is to have a single round of bidding, after which the auctioneer allocates the good to the winner. Such auctions are known as *one shot.* The second possibility is that the price starts low (often at a *reservation price)* and successive bids are for increasingly large amounts. Such auctions are known as *ascending.* The alternative - *descending* - is for the auctioneer to start off with a high value, and to decrease the price in successive rounds.

English auctions

English auctions are the most commonly known type of auction, made famous by such auction houses as Sothebys. English auction are *first-price, open cry, ascending* auctions:

- the auctioneer starts off by suggesting a *reservation price* for the good (which may be 0) - if no agent is willing to bid more than the reservation price, then the good is allocated to the auctioneer for this amount;
- bids are then invited from agents, who must bid more than the current highest bid - all agents can see the bids being made, and are able to participate in the bidding process if they so desire;
- when no agent is willing to raise the bid, then the good is allocated to the agent that has made the current highest bid, and the price they pay for the good is the amount of this bid.

What strategy should an agent use to bid in English auctions? It turns out that the dominant strategy is for an agent to successively bid a small amount more than the current highest bid until the bid price reaches their current valuation, and then to withdraw.

Simple though English auctions are, it turns out that they have some interesting properties. One interesting feature of English auctions arises when there is uncertainty about the true value of the good being auctioned. For example, suppose an auctioneer is selling some land to agents that want to exploit it for its mineral resources, and that there is limited geological information available about this land. None of the agents thus knows exactly what the land is worth. Suppose now that the agents engage in an English auction to obtain the land, each using the dominant strategy described above. When the auction is over, should the winner feel happy that they have obtained the land for less than or equal to their private valuation? Or should they feel worried *because no other agent valued the land so highly?* This situation, where the winner is the one who overvalues the good on offer, is known as the *winner's curse.* Its occurrence is not limited to English auctions, but occurs most frequently in these.

Dutch auctions

Dutch auctions are examples of *open-cry descending* auctions:

- the auctioneer starts out offering the good at some artificially high value (above the expected value of any bidder's valuation of it);
- the auctioneer then continually lowers the offer price of the good by some small value, until some agent makes a bid for the good which is equal to the current offer price;
- the good is then allocated to the agent that made the offer.

Notice that Dutch auctions are also susceptible to the winner's curse. There is no dominant strategy for Dutch auctions in general.

First-price sealed-bid auctions

First-price sealed-bid auctions are examples of one-shot auctions, and are perhaps the simplest of all the auction types we will consider. In such an auction, there is a single round, in which bidders submit to the auctioneer a bid for the good; there are no subsequent rounds, and the good is awarded to the agent that made the highest bid. The winner pays the price of the highest bid. There are hence no opportunities for agents to offer larger amounts for the good.

How should an agent act in first-price sealed-bid auctions? Suppose every agent bids their true valuation; the good is then awarded to the agent that bid the highest amount. But consider the amount bid by the second highest bidder. The winner could have offered just a tiny fraction more than the second highest price, and still been awarded the good. Hence most of the difference between the highest and second highest price is, in effect, money wasted as far as the winner is concerned. The best strategy for an agent is therefore to bid less than its true valuation. How *much* less will of course depend on what the other agents bid - there is no general solution.

Vickrey auctions

The next type of auction is the most unusual and perhaps most counterintuitive of all the auction types we shall consider. Vickrey auctions are *second-price sealed-bid* auctions. This means that there is a single negotiation round, during which each bidder submits a single bid; bidders do not get to see the bids made by other agents. The good is awarded to the agent that made the highest bid; however the price this agent pays is not the price of the highest bid, but the price of the *second highest* bid. Thus if the highest bid was made by agent *i*, who bid $9, and the second highest bid was by agent *j*, who bid $8, then agent *i* would win the auction and be allocated the good, *but agent i would only pay $8.*

Why would one even consider using Vickrey auctions? The answer is that Vickrey auctions make truth telling the dominant strategy: *a bidder's dominant strategy in a private value Vickrey auction is to bid his true valuation.* Consider why this is.

- Suppose that you bid *more* than your true valuation. In this case, you may be awarded the good, but you run the risk of being awarded the good but at more than the amount of your private valuation. If you win in such a circumstance, then you make a loss (since you paid more than you believed the good was worth).

- Suppose you bid *less* than your true valuation. In this case, note that you stand less chance of winning than if you had bid your true valuation. But, even if you do win, the amount you pay will not have been affected by the fact that you bid less than your true valuation, because you will pay the price of the second highest bid.

Thus the best thing to do in a Vickrey auction is to bid truthfully: to bid to your private valuation - no more and no less.

Because they make truth telling the dominant strategy, Vickrey auctions have received a lot of attention in the multiagent systems literature (see Sandholm (1999, p. 213) for references). However, they are not widely used in human auctions. There are several reasons for this, but perhaps the most important is that humans frequently find the Vickrey mechanism hard to understand, because at first sight it seems so counterintuitive. In terms of the desirable attributes that we discussed above, it is not *simple* for humans to understand.

Note that Vickrey auctions make it possible for *antisocial* behaviour. Suppose you want some good and your private valuation is $90, but you know that some other agent wants it and values it at $ 100. As truth telling is the dominant strategy, you can do no better than bid $90; your opponent bids $100, is awarded the good, but pays only $90. Well, maybe you are not too happy about this: maybe you would like to 'punish' your successful opponent. How can you do this? Suppose you bid $99 instead of $90. Then you still lose the good to your opponent - *but he pays $9 more than he would do ifyou had bid truthfully.* To make this work, of course, you have to be very confident about what your opponent will bid - you do not want to bid $99 only to discover that your opponent bid $95, and you were left with a good that cost $ 5 more than your private valuation. This kind of behaviour occurs in commercial situations, where one company may not be able to compete directly with another company, but uses their position to try to force the opposition into bankruptcy.

Expected revenue

There are several issues that should be mentioned relating to the types of auctions discussed above. The first is that of *expected revenue.* If you are an auctioneer, then as mentioned above, your overriding consideration will in all likelihood be to maximize your revenue: you want an auction protocol that will get you the highest possible price for the good on offer. You may well not be concerned with whether or not agents tell the truth, or whether they are afflicted by the winner's curse. It may seem that some protocols - Vickrey's mechanism in particular - do not encourage this. So, which should the auctioneer choose?

For private value auctions, the answer depends partly on the attitude to risk of both auctioneers and bidders (Sandholm, 1999, p. 214).

- For *risk-neutral bidders,* the expected revenue to the auctioneer is provably identical in all four types of auctions discussed above (under certain simple assumptions). That is, the auctioneer can expect on average to get the same revenue for the good using all of these types of auction.
- For *risk-averse bidders* (i.e. bidders that would prefer to get the good if they paid slightly more for it than their private valuation), Dutch and

first-price sealed-bid protocols lead to higher expected revenue for the auctioneer. This is because in these protocols, a risk-averse agent can 'insure' himself by bidding slightly more for the good than would be offered by a risk-neutral bidder.

- *Risk-averse auctioneers,* however, do better with Vickrey or English auctions.

Note that these results should be treated very carefully. For example, the first result, relating to the revenue equivalence of auctions given risk-neutral bidders, depends critically on the fact that bidders really do have private valuations. In choosing an appropriate protocol, it is therefore critical to ensure that the properties of the auction scenario - and the bidders - are understood correctly.

Lies and collusion

An interesting question is the extent to which the protocols we have discussed above are susceptible to lying and collusion by both bidders and auctioneer. Ideally, as an auctioneer, we would like a protocol that was immune to collusion by bidders, i.e. that made it against a bidder's best interests to engage in collusion with other bidders. Similarly, as a potential bidder in an auction, we would like a protocol that made honesty on the part of the auctioneer the dominant strategy.

None of the four auction types discussed above is immune to collusion. For any of them, the 'grand coalition' of all agents involved in bidding for the good can agree beforehand to collude to put forward artificially low bids for the good on offer. When the good is obtained, the bidders can then obtain its true value (higher than the artificially low price paid for it), and split the profits amongst themselves. The most obvious way of preventing collusion is to modify the protocol so that bidders cannot identify each other. Of course, this is not popular with bidders in open-cry auctions, because bidders will want to be sure that the information they receive about the bids placed by other agents is accurate.

With respect to the honesty or otherwise of the auctioneer, the main opportunity for lying occurs in Vickrey auctions. The auctioneer can lie to the winner about the price of the second highest bid, by overstating it and thus forcing the winner to pay more than they should. One way around this is to 'sign' bids in some way (e.g. through the use of a digital signature), so that the winner can independently verify the value of the second highest bid. Another alternative is to use a trusted third party to handle bids. In open-cry auction settings, there is no possibility for lying by the auctioneer, because all agents can see all other bids; first-price sealed-bid auctions are not susceptible because the winner will know how much they offered.

Another possible opportunity for lying by the auctioneer is to place bogus bidders, known as *skills*, in an attempt to artificially inflate the current bidding price. Shills are only a potential problem in English auctions.

Counterspeculation

Before we leave auctions, there is at least one other issue worth mentioning: that of *counterspeculation.* This is the process of a bidder engaging in an activity in order to obtain information either about the true value of the good on offer, or about the valuations of other bidders. Clearly, if counterspeculation was free (i.e. it did not cost anything in terms of time or money) and accurate (i.e. counterspeculation would accurately reduce an agent's uncertainty either about the true value of the good or the value placed on it by other bidders), then every agent would engage in it at every opportunity. However, in most settings, counterspeculation is not free: it may have a time cost and a monetary cost. The time cost will matter in auction settings (e.g. English or Dutch) that depend heavily on the time at which a bid is made. Similarly, investing money in counterspeculation will only be worth it if, as a result, the bidder can expect to be no worse off than if it did not counterspeculate. In deciding whether to speculate, there is clearly a tradeoff to be made, balancing the potential gains of counterspeculation against the costs (money and time) that it will entail. (It is worth mentioning that counterspeculation can be thought of as a kind of meta-level reasoning, and the nature of these tradeoffs is thus very similar to that of the tradeoffs discussed in practical reasoning agents as discussed in earlier chapters.)

7.3 Negotiation

Auctions are a very useful techniques for allocating goods to agents. However, they are too simple for many settings: they are *only* concerned with the allocation of goods. For more general settings, where agents must reach agreements on matters of mutual interest, richer techniques for reaching agreements are required. *Negotiation* is the generic name given to such techniques. In this section, we will consider some negotiation techniques that have been proposed for use by artificial agents - we will focus on the work of Rosenschein and Zlotkin (1994). One of the most important contributions of their work was to introduce a distinction between different types of negotiation domain: in particular, they distinguished between *task-oriented domains* and *worth-oriented domains.*

Before we start to discuss this work, however, it is worth saying a few words about negotiation techniques in general. In general, any negotiation setting will have four different components.

- A negotiation set, which represents the space of possible proposals that agents can make.
- A protocol, which defines the legal proposals that agents can make, as a function of prior negotiation history.
- A collection of strategies, one for each agent, which determine what proposals the agents will make. Usually, the strategy that an agent plays is *private:*

the fact that an agent is using a particular strategy is not generally visible to other negotiation participants (although most negotiation settings are 'open cry', in the sense that the actual proposals that are made *are* seen by all participants).

- A rule that determines when a deal has been struck, and what this agreement deal is.

Negotiation usually proceeds in a series of rounds, with every agent making a proposal at every round. The proposals that agents make are defined by their strategy, must be drawn from the negotiation set, and must be legal, as defined by the protocol. If agreement is reached, as defined by the agreement rule, then negotiation terminates with the agreement deal.

These four parameters lead to an extremely rich and complex environment for analysis.

The first attribute that may complicate negotiation is where *multiple issues* are involved. An example of a single-issue negotiation scenario might be where two agents were negotiating only the price of a particular good for sale. In such a scenario, the preferences of the agents are symmetric, in that a deal which is more preferred from one agent's point of view is guaranteed to be less preferred from the other's point of view, and vice versa. Such symmetric scenarios are simple to analyse because it is always obvious what represents a concession: in order for the seller to concede, he must lower the price of his proposal, while for the buyer to concede, he must raise the price of his proposal. In *multiple-issue* negotiation scenarios, agents negotiate over not just the value of a single attribute, but over the values of multiple attributes, which may be interrelated. For example, when buying a car, price is not the only issue to be negotiated (although it may be the dominant one). In addition, the buyer might be interested in the length of the guarantee, the terms of after-sales service, the extras that might be included such as air conditioning, stereos, and so on. In multiple-issue negotiations, it is usually much less obvious what represents a true concession: it is not simply the case that all attribute values must be either increased or decreased. (Salesmen in general, and car salesmen in particular, often exploit this fact during negotiation by making 'concessions' that are in fact no such thing.)

Multiple attributes also lead to an exponential growth in the space of possible deals. Let us take an example of a domain in which agents are negotiating over the value of n Boolean variables, $v_1, \ldots, v_n$. A deal in such a setting consists of an assignment of either true or false to each variable v_i. Obviously, there are 2^n possible deals in such a domain. This means that, in attempting to decide what proposal to make next, it will be entirely unfeasible for an agent to explicitly consider every possible deal in domains of moderate size. Most negotiation domains are, of course, much more complex than this. For example, agents may need to negotiate about the value of attributes where these attributes can have m possible values, leading to a set of m^n possible deals. Worse, the objects of negotiation may be individually very complex indeed. In real-world negotiation settings - such as labour disputes or (to pick a rather extreme example) the kind of negotiation that, at the time of writing, was still going on with respect to the political future of Northern Ireland, there are not only many attributes, but the value of these attributes may be laws, procedures, and the like.

The negotiation participants may even have difficulty reaching agreement on what the attributes under negotiation actually are - a rather depressing real-world example, again from Northern Ireland, is whether or not the decommissioning of paramilitary weapons should be up for negotiation. At times, it seems that the different sides in this long-standing dispute have simultaneously had different beliefs about whether decommissioning was up for negotiation or not.

Another source of complexity in negotiation is the number of agents involved in the process, and the way in which these agents interact. There are three obvious possibilities.

One-to-one negotiation. In which one agent negotiates with just one other agent. A particularly simple case of one-to-one negotiation is that where the agents involved have symmetric preferences with respect to the possible deals. An example from everyday life would be the type of negotiation we get involved in when discussing terms with a car salesman. We will see examples of such symmetric negotiation scenarios later.

-to-one negotiation. In this setting, a single agent negotiates with a number of other agents. Auctions, as discussed above, are one example of many-to-one negotiation. For the purposes of analysis, many-to-one negotiations can often be treated as a number of concurrent one-to-one negotiations.

Many-to-many negotiation. In this setting, many agents negotiate with many other agents simultaneously. In the worst case, where there are n agents involved in negotiation in total, this means there can be up to $n(n-1)/2$ negotiation threads. Clearly, from an analysis point of view, this makes such negotiations hard to handle.

For these reasons, most attempts to automate the negotiation process have focused on rather simple settings. Single-issue, symmetric, one-to-one negotiation is the most commonly analysed, and it is on such settings that I will mainly focus.

.1 Task-oriented domains

The first type of negotiation domains we shall consider in detail are the *task-oriented domains* of Rosenschein and Zlotkin (1994, pp. 29 52). Consider the following example.

> Imagine that you have three children, each of whom needs to be delivered to a different school each morning. Your neighbour has four children, and also needs to take them to school. Delivery of each child can be modelled as an indivisible task. You and your neighbour can discuss the situation, and come to an agreement that it is better for both of you (for example, by carrying the other's child to a shared destination, saving him the trip). There is no concern about being able to achieve your task by yourself. The worst that can happen is that you and your neighbour will not come to an agreement about setting up a car pool, in which case you are no worse off than if you were alone. You can only benefit (or do no worse) from your neighbour's tasks.
> Assume, though, that one of my children and one of my neighbours' children both go to the same school (that is, the cost of carrying out these two deliveries, or two tasks, is the same as the cost of carrying out one of them). Tt obviously makes sense for both children to be taken together, and only my neighbour or I will need to make the trip to carry out both tasks.
>
> What kinds of agreement might we reach? We might decide that I will take the children on even days each month, and my neighbour will take them on odd days; perhaps, if there are other children involved, we might have my neighbour always take those two specific children, while I am responsible for the rest of the children.
>
> (Rosenschein and Zlotkin, 1994, p. 29)

To formalize this kind of situation, Rosenschein and Zlotkin denned the notion of a *task-oriented domain* (TOD). A task-oriented domain is a triple

$$(T, Ag, c),$$

where

- T is the (finite) set of all possible tasks;
- $Ag = \{1, \dots, n\}$ is the (finite) set of negotiation participant agents;
- $c : p(T) \to \mathbb{R}^+$ is a function which defines the *cost* of executing each subset of tasks: the cost of executing any set of tasks is a positive real number.

The cost function must satisfy two constraints. First, it must be *monotonic*. Intuitively, this means that adding tasks never decreases the cost. Formally, this constraint is defined as follows:

If $T_1, T_2 \subseteq T$ are sets of tasks such that $T_1 \subseteq T_2$ then $c(T_1) \leqslant c(T_2)$.

The second constraint is that the cost of doing nothing is zero, i.e. $c(\emptyset) = 0$.

An *encounter* within a task-oriented domain (T, Ag, c) occurs when the agents Ag are assigned tasks to perform from the set T. Intuitively, when an encounter occurs, there is potential for the agents to reach a deal by reallocating the tasks amongst themselves; as we saw in the informal car pool example above, by reallocating the tasks, the agents can potentially do better than if they simply performed their tasks themselves. Formally, an encounter in a TOD *(T,Ag, c)* is a collection of tasks

where, for all *i,* we have that $i \in Ag$ and $T_i \subseteq T$. Notice that a TOD together with an encounter in this TOD is a type of *task environment,* of the kind we saw in Chapter 2. It defines both the characteristics of the environment in which the agent must operate, together with a task (or rather, set of tasks), which the agent must carry out in the environment.

Hereafter, we will restrict our attention to one-to-one negotiation scenarios, as discussed above: we will assume the two agents in question are {1,2}. Now, given an encounter $\langle T_1, T_2 \rangle$,a *deal* will be very similar to an encounter: it will be an allocation of the tasks T_1 u T_2 to the agents 1 and 2. Formally, a pure deal is a pair $\langle D_1, D_2 \rangle$ where $D_1 \cup D_2 = T_1 \cup T_2$. The semantics of a deal $\langle D_1, D_2 \rangle$ is that agent 1 is committed to performing tasks D_1 and agent 2 is committed to performing tasks D_2.

The *cost* to agent *i* of a deal *d* = is defined to be *c{Di),* and will be denoted *costi (5).* The *utility* of a deal *5* to an agent *i* is the difference between the cost of agent *i* doing the tasks T_i that it was originally assigned in the encounter, and the cost $cost_i(\delta)$of the tasks it is assigned in *8:*

$$utility_i(\delta) = c(T_i) - cosii(S).$$

Thus the utility of a deal represents how much the agent has to gain from the deal; if the utility is negative, then the agent is *worse off* than if it simply performed the tasks it was originally allocated in the encounter.

What happens if the agents *fail* to reach agreement? In this case, they must perform the tasks $\langle T_1, T_2 \rangle$ that they were originally allocated. This is the intuition behind the terminology that the *conflict deal,* denoted 0, is the deal $\langle T_1, T_2 \rangle$ consisting of the tasks originally allocated.

The notion of *dominance,* as discussed in the preceding chapter, can be easily extended to deals. A deal δ_1 is said to dominate deal *82* (written *8* > δ_2) if and only if the following hold.

(1) Deal δ_1 is at least as good for every agent as δ_2:

$$\text{Vi} \quad \text{E} \quad \{1,2\}, utility_i(\delta \geqslant \quad utility_i(\delta_2).$$

(2) Deal δ_1 is better for some agent than δ_2:

$$\exists i \quad \text{E} \quad \{1,2\}, utility_i(\delta_1)$$

If deal δ_1 dominates another deal δ_2, then it should be clear to all participants that δ_1 is better than δ_2. That is, all 'reasonable' participants would prefer δ_1 to

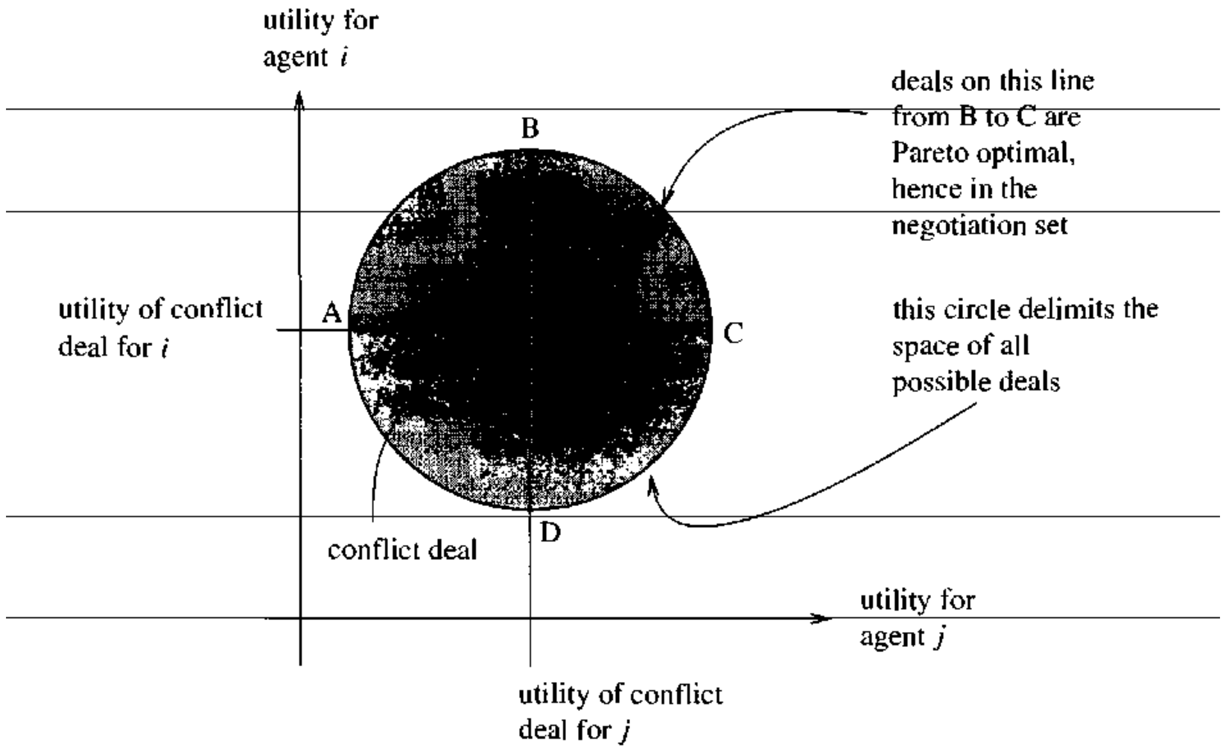

Figure 7.1 The negotiation set.

δ_2. Deal δ_1 is said to weakly dominate δ_2 (written $\delta_1 \succ$ *82)* if at least the first condition holds.

A deal that is not dominated by any other deal is said to be *pareto optimal.* Formally, a deal *8* is pareto optimal if there is no deal *8'* such that *8'* > *8.* If a deal is pareto optimal, then there is no alternative deal that will improve the lot of one agent except at some cost to another agent (who presumably would not be happy about it!). If a deal is not pareto optimal, however, then the agents could improve the lot of at least one agent, without making anyone else worse off.

A deal *8* is said to be *individual rational* if it weakly dominates the conflict deal. If a deal is *not* individual rational, then at least one agent can do better by simply performing the tasks it was originally allocated - hence it will prefer the conflict deal. Formally, deal *8* is individual rational if and only if $\delta \succ$ ©.

We are now in a position to define the space of possible proposals that agents can make. The *negotiation set* consists of the set of deals that are (i) individual rational, and (ii) pareto optimal. The intuition behind the first constraint is that there is no purpose in proposing a deal that is less preferable to some agent than the conflict deal (as this agent would prefer conflict); the intuition behind the second condition is that there is no point in making a proposal if an alternative proposal could make some agent better off at nobody's expense.

The intuition behind the negotiation set is illustrated in Figure 7.1. In this graph, the space of all conceivable deals is plotted as points on a graph, with the utility to i on the y-axis, and utility to j on the x-axis. The shaded space enclosed by points

A, B, C, and D contains the space of all possible deals. (For convenience, I have illustrated this space as a circle, although of course it need not be.) The conflict deal is marked at point E. It follows that all deals to the left of the line B-D will not be individual rational for agent *j* (because *j* could do better with the conflict deal). For the same reason, all deals below line A-C will not be individual rational for agent *i*. This means that the negotiation set contains deals in the shaded area B-C-E. However, not all deals in this space will be pareto optimal. In fact, the only pareto optimal deals that are also individual rational for both agents will lie on the line B-C. Thus the deals that lie on this line are those in the negotiation set. Typically, agent *i* will start negotiation by proposing the deal at point B, and agent *j* will start by proposing the deal at point C.

The monotonic concession protocol

The protocol we will introduce for this scenario is known as the *monotonic concession protocol* (Rosenschein and Zlotkin, 1994, pp. 40, 41). The rules of this protocol are as follows.

- Negotiation proceeds in a series of rounds.
- On the first round, both agents simultaneously propose a deal from the negotiation set.
- An agreement is reached if the two agents propose deals δ_1 and δ_2, respectively, such that either (i) $utility_1(\delta_2) \geqslant utility_1(\delta_1)$ or (ii) $utility_2(\delta_1) \geqslant utility_2(\delta_2)$, i.e. if one of the agents finds that the deal proposed by the other is at least as good or better than the proposal it made.

  If agreement is reached, then the rule for determining the agreement deal is as follows. If both agents' offers match or exceed those of the other agent, then one of the proposals is selected at random. If only one proposal exceeds or matches the other's proposal, then this is the agreement deal.

  If no agreement is reached, then negotiation proceeds to another round of simultaneous proposals. In round $u + 1$, no agent is allowed to make a proposal that is less preferred by the other agent than the deal it proposed at time u.

  If neith [illegible] a concession in some round $u > 0$, then negotiation terminates, with the conflict deal.

It should be clear that this protocol is effectively *verifiable:* it is easy for both parties to see that the rules of the protocol are being adhered to.

Using the monotonic concession protocol, negotiation is guaranteed to end (with or without agreement) after a finite number of rounds. Since the set of possible deals is finite, the agents cannot negotiate indefinitely: either the agents will reach agreement, or a round will occur in which neither agent concedes. However, the protocol does not guarantee that agreement will be reached *quickly*. Since the number of possible deals is $O(2^{|T|})$, it is conceivable that negotiation will continue for a number of rounds exponential in the number of tasks to be allocated.

The Zeuthen strategy

So far, we have said nothing about how negotiation participants might or should behave when using the monotonic concession protocol. On examining the protocol, it seems there are three key questions to be answered as follows.

- What should an agent's first proposal be?
- any given round, *who should concede?*
- If an agent concedes, then *how much* should it concede?

The first question is straightforward enough to answer: an agent's first proposal should be its most preferred deal.

With respect to the second question, the idea of the Zeuthen strategy is to measure an agent's *willingness to risk conflict.* Intuitively, an agent will be more willing to risk conflict if the difference in utility between its current proposal and the conflict deal is low.

In contrast, if the difference between the agent's current proposal and the conflict deal is high, then the agent has more to lose from conflict and is therefore less willing to risk conflict - and thus should be more willing to concede.

Agent i's willingness to risk conflict at round t, denoted $risk_i^t$, is measured in the following way (Rosenschein and Zlotkin, 1994, p. 43):

$$risk_i^t = \frac{\text{utility } i \text{ loses by conceding and accepting } j\text{'s offer}}{\text{utility } i \text{ loses by not conceding and causing conflict}}.$$

The numerator on the right-hand side of this equation is defined to be the difference between the utility to i of its current proposal, and the utility to i of j's current proposal; the denominator is defined to be the utility of agent i's current proposal. Until an agreement is reached, the value of $risk_i^t$ will be a value between 0 and 1. Higher values of $risk_i^t$ (nearer to 1) indicate that i has less to lose from conflict, and so is more willing to risk conflict. Conversely, lower values of $risk_i^t$ (nearer to 0) indicate that i has more to lose from conflict, and so is less willing to risk conflict.

Formally, we have

$$risk_i^t = \begin{cases} 1 & \text{if } utility_i(\delta_i^t) = 0, \\ \dfrac{utility_i(\delta_i^t) - utility_i(\delta_j^t)}{utility_i(\delta_i^t)} & \text{otherwise.} \end{cases}$$

The idea of assigning risk the value 1 if $utility_i(\delta_i^t) = 0$ is that in this case, the utility to i of its current proposal is the same as from the conflict deal; in this case, i is completely willing to risk conflict by not conceding.