

Chapter 2

Game Theory in Neuroeconomics

Claudia Civali and Daniel R. Hawes

(Spade): If you kill me, how are you going to get the bird? If I know you can't afford to kill me till you have it, how are you going to scare me into giving it to you?

(Gutman): "Well, sir, there are other means of persuasion besides killing and threatening to kill."

(Spade): "Sure, but they're not much good unless the threat of death is behind them to hold the victim down. See what I mean? If you try something I don't like I won't stand for it. I'll make it a matter of your having to call it off or kill me, knowing you can't afford to kill me."

(Gutman): "I see what you mean. That is an attitude, sir, that calls for the most delicate judgment on both sides, because, as you know, sir, men are likely to forget in the heat of action where their best interests lie and let their emotions carry them away."

—The Maltese Falcon

Abstract Game theory and contemporary decision theory provide the mathematical foundation of economics. Neuroeconomics, which principally concerns itself with the integrative study of brain, mind and behavior, builds on this mathematical foundation while also drawing heavily from the repository of experimental paradigms that have grown out of economic game theory and behavioral economics. Game theory is central to neuroeconomics primarily because it constitutes a formal mathematical framework with which to bridge insights occurring at different levels of neuroeconomic analysis. In particular, game theoretic principles can be used to express neuroscientific ideas about the brain, psychological concepts regarding the human mind, and economic predictions of human behavior, thereby making these different ideas more rigorously relatable to each other. In this chapter we provide a nontechnical introduction to game theory and its relation to neuroeconomics. It has been written as an overview of the basic concepts most likely to be encountered in neuroeconomic research. The first part of the chapter introduces the reader to the

C. Civali (✉)

Donders Institute for Brain, Cognition and Behaviour, Radboud University,

Nijmegen, Netherlands

e-mail: c.civali@donders.ru.nl

D.R. Hawes

Institute of Food and Resource Economics, University of Bonn, Bonn,

Deutschland

e-mail: daniel.hawes@uni-bonn.de

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M. Reuter and C. Montag (eds.), *Neuroeconomics*, Studies in Neuroscience, Psychology and Behavioral Economics, DOI 10.1007/978-3-642-35923-1_2

basic concepts and philosophical underpinnings of game theory in relation to neuroeconomics. The second part is an introduction and discussion of common games, including the games featured in the other chapters of this book.

2.1 Introduction

In the well-known movie “The Maltese Falcon” (Wallis and Huston 1941) Humphrey Bogart’s character (Spade) attempts to ‘call bluff’ on his adversaries’ threats. He does so by what amounts to game theoretic reasoning—namely by putting into relation each man’s objectives, their individual beliefs, and their shared knowledge of the situation—and deduces that the adversary, Gutman, cannot possibly afford to kill him for risk of never learning the Maltese Falcon’s whereabouts. Gutman of course concludes with the cautioning appeal to keep in mind the potential for internal conflict between reason and emotion, and how rational objectives may become lost in its wake.

Neuroeconomics relates to this scene as an extension of economic analysis, traditionally preoccupied with the prediction of behavior, into the realm of the brain and the mind (the internal processes that give rise to behavior). Neuroeconomics is inherently interdisciplinary, but draws most heavily from economic decision theory, psychology, and neuroscience. Game theory, as the mathematical foundation of economic decision theory, is central to neuroeconomics, because of the relatively new disciplines’ intellectual history (i.e., because neuroeconomics lends from economics, and economics uses game theory), but also because it has the potential to function as the mathematical foundation upon which neuroeconomic theory might be developed further into a discipline of its own right (i.e., the properties of game theory make it an attractive candidate for trying to develop an integrative theory of brain, mind, and behavior).

The purpose of this chapter is to introduce researchers coming to neuroeconomics from fields other than economics to the basic principles and ideas that feature in game theory. While outlining the basic tenets of game theory, we also attempt to draw philosophical and historical connections that link game theory to the goals and of neuroeconomics.

Game theory, generally speaking, is the study of mathematical objects whose states and properties interact. At the level of neuroscience, game theory could be used to describe the interactive or competitive firing of neuron populations. At the level of psychology, game theory could be used to describe the emergence of mental states in relation to interacting cognitive processes, or the emergence of behavior from competing mental states. Traditionally, in economic analysis, game theory has been used to predict the behavior of multiple, interacting, intelligent decision-makers. Hence, game theory can be viewed as a general tool for the logical consideration of strategic and nonstrategic relationships at multiple levels of analysis, as long as the concepts being used have representation as numbers and the relationships are closed or bounded correspondences. Economic examples, which

represent the mathematical objects of game theory as the behaviors of intelligent decision-makers, are generally intuitive, instructive, and easy to develop, wherefore this consideration forms the common approach in most textbooks, and also in this chapter. However, we hope to draw the reader's attention to the fact that game theory itself, being a mathematical language and logic system, has far wider application and that fundamental issues regarding measurement of utility through games, and how this relates to theory development in physics, remains outside of the scope of this chapter. The classic book *Theory of Games and Economic Behavior* (in particular chapter 1) remains invaluable on this account (von Neumann and Morgenstern 1944).

As neuroeconomics becomes more consolidated as a stand-alone discipline, we expect the importance of game theory for neuroeconomics to increase, and have reasoned hope for the potential of game theory to function as a bridge across different levels of brain–mind behavior analysis. This latter part, concerning the future of game theory in neuroeconomics, remains personal conjecture and is only hinted at or mentioned in passing throughout this chapter; however, it informs much of our thinking in choosing which elements of game theory to focus on for this introduction, and how to present the basic principles. It makes sense, therefore, to provide a quick note on our definition of neuroeconomics.

Neuroeconomics as an interdisciplinary scientific approach aimed at discovering/creating a unified theory of human behavior and cognition, via integrative study of mind, brain, and behavior relationships.

Practically, the neuroeconomic enterprise combines concepts, methods, and technological tools from neuroscience (see Chap. 8) with formal analysis of decision-making, typically drawing heavily from economic decision theory as well as psychology.

As a procedure, neuroeconomics aims to experimentally link the neurophysiological and behavioral constituents of the decision process to each other, and then conceptually relate these links to psychological concepts of mental activity via formal models, typically in the tradition of economics and decision theory.

With this definition of neuroeconomics in place, the formal models developed within game theory enable mathematically precise descriptions of the decision process, which in turn allow prediction, specification, and comparison of neural activity presumed to underlie decision-making. Additionally, experimental paradigms developed within experimental game theory (i.e., games) are prominently featured in neuroeconomics research, where the goal is often to differentiate between competing economic models of the decision process (Glimcher and Rustichini 2004; Rustichini 2005; Camerer et al. 2005), or to investigate competing descriptions of mental processes thought to underlie a particular kind of decision or behavioral phenomenon.

Because it is a common source of confusion, the final note of this introduction points to game theories' conceptual birth in expected utility theory and connection to the economic idea of rational decision-making (Mongin 1997): As will be discussed later, strict economic rationality is not necessary for game theoretic inquiry, and many game theoretic applications in neuroeconomics are explicitly

geared toward understanding decision processes for which individuals systematically violate the predictions of rational choice theory and expected utility maximization in one way or another. Furthermore, the interested reader is encouraged to consider differences in the economic meaning of rationality compared to the noneconomic colloquial meaning of rationality, for example, by consulting Anthony Downs' book "An economic theory of democracy." (1957).

The remainder of this chapter elaborates on the basic elements described in the above introduction. It concludes with a compendium of games most commonly encountered in the neuroeconomics literature, including a digest of each of the games featured in this book.

2.1.1 Basic Terms and Definitions

This chapter is a nontechnical introduction to game theory¹; however, the main strengths of game theory derive precisely from its mathematical exactness and rigorous definitions, wherefore some minimal recourse to formal terminology appears unavoidable. We therefore begin by introducing some basic terms and definitions that will appear throughout this chapter, first among which are those that describe an economic *Game*.

A formal game consists of three basic objects:

1. **Players** are independent decision-makers, mathematically represented in terms of their utility functions; i.e., by a function that assigns ordinal preference rank to all possible outcomes of the game.
2. **Actions** are full descriptions of the actions each player may take during the game. These action descriptions may differentiate between different points of time, situational circumstances or—more generally—*stages* of the game.
3. **Payoffs** are full descriptions of the outcome (and consequently utility) experienced by each player for each possible combination of actions that may occur during the game.

Additional objects used to describe games may include

- (a) **Information Sets** are full descriptions of the information available to each player in each stage of the game. Information pertains to the actions available to the players, their utility functions, as well as the current history and possible trajectory of stages in the game.
- (b) **Environments** are nonstrategic mechanisms capable of influencing any of the above elements of the game, typically in a probabilistic manner. For example, the environment may impose random restrictions on what type of actions are

¹Comprehensive, technical treatments can be found for example in Myerson (2013) and Osborne and Rubinstein (1994).

available at a given stage of the game, or may influence the payoff distribution for game outcomes.

- (c) **Strategies** are probability distributions over all actions for each stage of the game. Strategies are full descriptions of what action should be chosen for each possible stage of the game. A strategy can describe a specific action for each stage, in which case it is referred to as a pure strategy. Alternatively, a strategy may assign probabilities to multiple actions for any given stage, in which case it is referred to as a mixed strategy. Importantly, a strategy specifies an action or mixture of actions for every possible contingency of the game.

In nondegenerate² games, the actions taken by all of the players collectively interact to determine the payoffs and consequent utilities experienced by each player individually. This gives rise to the strategic considerations, which lie at the heart of game theory.

The major objectives of game theoretic inquiry may therefore be described as the aim to:

1. Formulate applicable game descriptions for real-world decision problems;
2. Develop and apply solution concepts to positively describe or normatively prescribe the strategic reasoning processes that are used by players in game situations;
3. Develop, refine, and apply equilibrium concepts that describe stable patterns of strategic reasoning and behavior between the players.
4. Identify the existence and properties of such equilibriums.

The above elements of a game are described and presented in either a so-called *Extensive Form*, or as a so-called *Normal Form* representation.

Extensive Form representations are depictions of games by the way of mathematical graphs. In these graphs the nodes represent the different stages of the game, and the edges (the lines connecting the nodes) represent the actions that lead to each stage. Extensive Form games specify exactly the possible sequence of actions and their resulting outcomes for a game, and are therefore particularly useful when the order in which players choose during the game is relevant to its outcome. An annotated example is given in Fig. 2.1a.

Normal Form representations of games are more commonly used for games in which the order of moves is irrelevant, as is the case in so-called one-shot, simultaneous move games, i.e., games in which the resulting outcome is determined by considering all chosen actions simultaneously.³ Normal Form games are presented as matrices, with each cell of the game matrix containing a vector of final

²That is, games that can not be reduced to sets of mere one-player decision problems in which the actions of other players are irrelevant to each players utility.

³Think for example of a secret ballot election, in which each player enters a vote into a computer, and the computer then decides the election outcome by considering all such submitted votes.

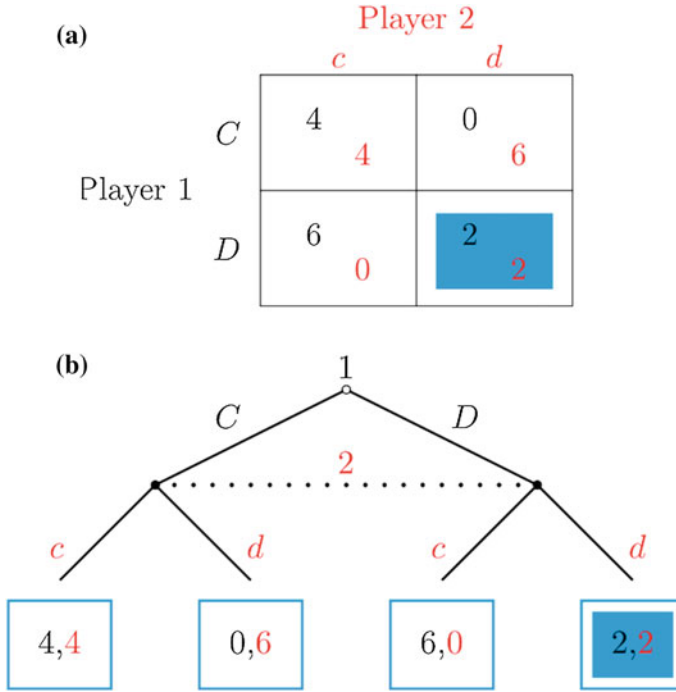


Fig. 2.1 **a** Generic Prisoner's Dilemma (normal form). Rows indicate actions available to Player 1 ($\{C, D\}$) and columns indicate actions of Player 2 ($\{c, d\}$). Cells list the utility of each combination of actions. Utility to player 1 is listed first in *black font*. Utility to player 2 is listed second and using *red font*. We have *highlighted* the Nash equilibrium outcome in the *bottom right cell*, corresponding to choice of *D*, and *d* by the two players. **b** Generic Prisoner's Dilemma (extensive form). For illustration we also show a strategic form version of the PD. Nodes indicate players' "turns" in the game. Player 1 moves first at the initial node of the game (open circle). Edges indicate actions available at each node ($\{C, D\}$ for player 1, $\{c, d\}$ for player 2). Dotted lines connecting nodes indicate information sets. Two nodes belonging to the same information set cannot be distinguished by the player. Hence, player 2—at the time of her move—does not know whether player one has chosen *C* or *D*. Final nodes contain the utility to each player. We have again highlighted the Nash equilibrium for this game. Although the extensive form and strategic form of the prisoner's dilemma are equivalent, not all extensive form games can be transformed into an equivalent normal form game

payoffs for each possible combination of actions (for all players) that may occur in the game.⁴ An annotated example is given in Fig. 2.1b.

The well-known Prisoner's Dilemma (PD) provides a useful example for demonstrating the concepts introduced thus far, and both Fig. 2.1a, b are depictions of this game. The PD is a one-shot, simultaneous move game between two players. Each player in the game has two actions available to him or her. We call these

⁴Note that all extensive form games can be transformed into normal form, but not all normal form games may have an equivalent extensive form; hence there also exists a qualitative difference.

actions $\{C\}$ and $\{D\}$ for player 1, and $\{c, d\}$ for player 2. The intuition behind the PD was originally suggested by Flood and Dreshner in the 1950s, later formalized by Albert Tucker (Poundstone 1992), and goes as follows: two criminals are being questioned by the police; both are facing the choice of whether to defect ($\{D\}$ or $\{d\}$) on their partner in crime by providing incriminating evidence to the police, or to remain cooperative ($\{C\}$, or $\{c\}$) by not revealing any information during interrogation. The possible actions to each player are therefore to cooperate or to defect ($\{C, D\}$) for player one, as well as for player two ($\{c, d\}$). In the case that both prisoners remain cooperative ($\{C, c\}$) the police lacks evidence for a full conviction and both criminals go to jail for only a short period of time; in the case that both prisoners defect on each other ($\{D, d\}$), they both land in jail. The interesting scenario that creates the dilemma results from what happens when one player defects while the other remains cooperative ($\{C, d\}$ or $\{D, c\}$): in this case the defector goes free entirely, while the defected upon goes to jail for an extended period of time. The possible outcomes to the game are therefore ($\{C, c\}$, $\{C, d\}$, $\{D, c\}$, and $\{D, d\}$), and the payoffs are given by the utility experienced for the differing amounts of jail time (in the example we let these utilities be 0, 2, 4, and 6). Assuming that both players prefer less time in jail to more time in jail (i.e., they prefer higher utility values among the outcomes in Fig. 2.1b), each player in this game fares best when he or she is the only one to defect, and worst if he or she is the only one to cooperate. Additionally, each player also prefers the outcome of mutual cooperation to the outcome of mutual defection.

Standard game theoretic reasoning predicts an equilibrium outcome for the Prisoner's Dilemma in which both players defect. This is because the outcome from meeting cooperation by the other player with defection (i.e., the best outcome) is preferred to the outcome from mutual cooperation; at the same time meeting defection by the other player with defection also is preferred to being the only cooperator in the game (i.e., the worst outcome). Hence defecting is a best response to whatever the other player does, and thus mutual defection becomes an equilibrium response in the game.

The terms *best response* and *equilibrium* deserve special note in this context, as they relate to a very particular solution concept in game theory, known as *Nash Equilibrium*, Nash Solution Concept, or Best Response Equilibrium. This concept defines equilibriums for finite noncooperative⁵ games as instances in which each player is playing a *best response* given the strategies being played by all other players in the game. A strategy, in turn, is defined as a best response if and only if its expected utility is at least as large as that obtained from any other possible strategy the player may play.⁶ Hence, in Nash equilibrium no player has any

⁵Game theory divides games into cooperative and noncooperative types. All of the games in this chapter are noncooperative games, and we therefore do not spend a lot of time discussing the difference between the two classes of games, which can be found elsewhere (e.g., Myerson 2013).

⁶The concept is named after John Nash, among other contributions, for his work on such equilibrium points in n -person games (Nash 1950).

incentive to unilaterally change his or her chosen response in the game, since it is a best response to what all other players are choosing at the time.

Returning to the PD, it is also worth noting that defection is a so-called dominant strategy for both players. This means that defecting is optimal regardless of what other players choose. Not all games have dominant strategies, however, and they are not necessary for Nash equilibrium. We will see examples of such games later in this chapter.

2.1.2 Rationality and Expected Utility Maximization

Standard game theoretic solutions to decision situations such as the Prisoner's Dilemma prescribe the optimal behavior of a rational decision-maker with unlimited analytical resources under the goal of utility maximization. However, human analytical resources are necessarily limited, introspection may be noisy, preferences may be uncertain, and any host of context-dependent affective responses may contribute to the decision process. Furthermore, decision-makers may rely on heuristics and intuitions (i.e., emotions or gut feelings) in order to reduce cognitive costs (Simon 1972, 1990; Tversky and Kahneman 1974; Damasio et al. 1991; Gigerenzer 2004; Glöckner and Betsch 2008; Glöckner and Hochman 2011). Such psychological features and behavioral strategies may be behaviorally indistinguishable from rational choice behavior in some contexts, but lead to systematic biases and inconsistencies in others. Investigation of such behavior has a long history in economics (e.g., Allais 1979; Ellsberg 1961; Loomes and Sugden 1982), and has given rise to extensions (e.g. Friedman and Savage 1948; Aumann 1997), and modifications such as bounded rationality (Selten 1990) and Prospect Theory (Kahneman and Tversky 1979). Consequently, economic theory has produced a wealth of models and theory refinements that individually address instances in which standard economic model possess poor predictive validity.⁷ To the extent that none of these competing models and refinements approaches the economic ideal of a unified theory of human behavior, neuroeconomics is seen as a disciplined approach to answering unresolved questions in economics: for example by juxtaposing competing models [e.g., by investigating whether a unified system, or separate systems compute the value for present versus future rewards (McClure et al. 2004)]; by investigating the rules that govern for whom, when and under which circumstances one model, or model specification, is more applicable than another [e.g., by generating insights into the neurobiology underlying different types of decision-makers (Coricelli and Nagel 2009; Bhatt et al. 2010), and learned strategic behaviors (Hawes et al. 2012)]; or by helping to establish the precise role

⁷Note that Economic Theory is primarily concerned with generalizable predictive validity, and that content validity regarding the process via which a decision is actually made, is at best secondary, but probably irrelevant, to as-if modeling in economics.

of affect and social sensitivity during decision-making (Van't Wout et al. 2006; Civali et al. 2010).

Despite being strongly linked to expected utility theory as formulated by Von Neuman and Morgenstern, game theory features prominently in the neuroeconomic endeavors described above, as game theory itself allows for any number of postulatory models of players behaviors, and the details of the behavioral models used to describe the decision-maker may differ across studies. For example, players may be thought to be entirely rational⁸ and self-interested, while updating their beliefs in complete accordance to Bayes rule, eventually converging on Nash equilibrium behavior (Kalai and Lehrer 1993). Alternatively, players may be modeled as possessing *bounded rationality*, may be compassionate to others, or may update beliefs with respect to subjective probability representations (Rabin 1993; Camerer et al. 2011). Similarly, different definitions for what comprises equilibrium behavior (i.e., different types of equilibriums) exist in game theory, therefore extending and generalizing the concept of Nash equilibrium (e.g., Perfect Nash Equilibrium in dynamic games, Correlated Equilibrium, Trembling Hand Equilibrium, etc.).

Despite this flexibility of game theory, rational choice and expected utility theory remain the principal departing points for most neuroeconomic investigations of behavior, where, at the very least, expected utility theory functions as a benchmark for comparison for any neuroeconomic investigation of alternative models. Because of this, and because the games discussed in this book are conceptually founded in the expected utility framework, our concluding compendium considers each game with respect to expected utility maximization and Nash equilibrium. Before explaining precisely what these terms mean, we want to add brief mention of some alternative frameworks that feature prominently in neuroeconomics, but are only peripherally considered in the compendium of games that concludes this chapter.

2.1.3 *Alternatives to Expected Utility Theory*

Insights developed under the frameworks of Bounded Rationality, Prospect Theory, and under the research agenda often labeled Behavioral Economics, are particularly relevant to the research domains we have mentioned above, and have been consequentially influential in neuroeconomics, and neuroeconomic research on games: *Bounded Rationality* as introduced originally by Simon (1955) and Gigerenzer and Selten (2002) takes into account cognitive limitations of the decision-maker. The theory posits that human beings are limited in their capacity for solving complex problems and for processing large quantities of information, wherefore useful game

⁸Rationality in the economic sense means that the decision-maker has preferences that are complete and transitive, or acyclical. This means that the decision-maker can rank all alternatives according to an ordinal metric, and that within this ranking whenever A is preferred to B, and B is preferred to C, then A will be preferred to C also.

theoretic descriptions must include explicit consideration of how players decide upon which information to consider, which information to ignore, and when to rely on simpler heuristics for decision-making. Such questions of which types of information are attended to during the decision process and how integration occurs for information derived from multiple sources, or pertaining to multiple dimensions of the decision problem, lay at the core of neuroeconomic research. Additionally, researchers have recently begun to investigate stable individual differences in how individuals use information during decision-making (e.g., Burks et al. 2009; Engelmann and Tamir 2009).

Prospect Theory, developed by psychologists Kahneman and Tversky (1979) in the context of risky decision-making is similarly central to neuroeconomics. In a nutshell, Prospect Theory argues that utilities of losses are computed differently from utilities derived from gains, and that objective probabilities undergo a subjective weighting during the decision process. The precise nature in which value and probability are represented in the brain continues to be a core theme of neuroeconomic research. Various psychological phenomena have been explained within Prospect Theory, such as the *framing effect*, which considers differences in choice behavior depending on whether the same problem is described in terms of gains or losses, and the *endowment effect*, also known as the fact that people ascribe more value to things that they own. These cognitive biases have also been subject of neuroeconomics investigation (De Martino et al. 2006; Knutson et al. 2008).

Finally, a large body of recent work spearheaded by researchers such as Colin Camerer, George Loewenstein, Matthew Rabin, Ernst Fehr, and Simon Gächter has tried to go even further than Prospect Theory in its attempt to import insights from Psychology into economic thinking. This research has drawn strongly from insights in Personality Psychology and Social Psychology to investigate the way in which humans respond to incentives and formulate beliefs during complex decision-making, especially social interactions. Influential work in this field has tried to explain the role of nonreciprocal altruism, perceptions of fairness, inequity aversion, and competitive motives during the choice process, and has thus provided novel insights to neuroeconomics regarding the investigation of a person's utility (e.g., Rabin 1993; Fehr and Schmidt 1999; Camerer 2003). Work in this field also investigates social phenomena such as the occurrence of economic bubbles in bidding competitions, or how beliefs about other player's mental abilities influence the level of reasoning and information processing that is applied to game situations. As evidenced by other chapters of this book, economic games, such as multi-person auctions or the Ultimatum Game (see Sect. 2.2.6 of this chapter), feature prominently in this type of research, and are also used as tools in neuroeconomic investigations of the role of social context and cognitive skills during decision-making.

2.2 Compendium of Common Games

The main body of this book chapter has introduced game theory as a powerful and flexible, philosophically rich framework for neuroeconomic research on decision-making. We have purposefully emphasized the distinction between game theory and the economic (*as-if*) notion of rationality, since we have found that conflation of these two concepts can confuse non-Game Theorists about the applicability of game theory to the *as-is* investigation of human behavior. Hoping to have thus preempted such confusion, we will however continue our discussion of games with reference to the common framework within which players are thought to be *rational expected utility maximizers* in the Von Neumann and Morgenstern sense. This means, first, that players consider a probability distribution of possible outcomes and their attendant payoffs. Second, the expected utility of an action is then determined by integrating the utility of the payoffs with respect to these probabilities. In the discrete case, this means that the utility from each possible outcome following an action is weighted by the probability assigned to it by the action. Finally, the sum of these weighted utilities then forms the players expected utility. Players are **expected utility maximizers** if they compute expected utilities in this way and always choose the action that results in the highest expected utility. Players are considered **rational** in the economic sense if they have complete, and transitive, preferences.

Furthermore, unless stated explicitly, we will consider only *Nash equilibrium* solutions to the games we discuss. **Nash equilibriums** are defined for finite non-cooperative games, and constitute instances in which each player is playing a *best response* given the strategies being played by all other players. A strategy, in turn, is a best response if, and only if, its expected utility is at least as large as that obtained from any other possible strategy.

2.2.1 Matching Pennies

Intuition: The Matching Pennies game features two players with identical choice between two actions. One player receives a preferred outcome whenever both players match on their actions, and incurs a less preferred outcome whenever they mismatch on their actions. The other player incurs the preferred outcome as a result of the mismatch, but incurs the less preferred outcome from a match. In the notation of the example (Fig. 2.2), matches occur when player 1 chooses U and player 2 chooses L, or when player 1 chooses D and player 2 chooses R. All other combinations produce mismatches.

In the matching pennies game, the actions that lead to a preferred outcome for one player, lead to the less preferred outcome for the other. This property is typically referred to as zero-sum (since the properties of the game remain under payoffs

		Player 2	
		<i>l</i>	<i>r</i>
Player 1	<i>U</i>	-1 1	1 -1
	<i>D</i>	1 -1	-1 1

Fig. 2.2 Generic Matching Pennies. Player 1 chooses between U(p) and D(own), while player 2 chooses between l(left) and r(right). Player 1 wins when actions match ($\{U, l\}$ and $\{D, r\}$), player 2 wins under the alternative outcomes

that add up to zero for each outcome), and the Matching Pennies game is often cited as a quintessential example of such games.

Equilibrium Solutions: The Matching Pennies game is a two-action version of popular games such as “Rock, Paper, Scissors”, “Morra”, or “oddsandevens”. Like with these common games a player’s most promising strategy in Matching Pennies is to remain unpredictable to the opposing player while also exploiting any predictability they may observe with their opponent. More concrete, the Matching Pennies game does not have best response equilibrium in pure strategies. Using the notation of the normal form example in Fig. 2.2, whenever player 1 plays a strategy in which U is played with a probability $p > 0.5$ player 2 may improve his payoffs by always choosing R. And whenever player 1 chooses U with probability $p < 0.5$, player 2 can exploit this by always choosing L. The same is true in likeness for player 2 choosing either L or R with probability different from $p = (1 - q) = 0.5$. Crucially, whenever player 1 randomizes between U and D with equal probability ($p = q = 0.5$) player 2 is entirely indifferent between any probability over R and L. Likewise player 1 has equal expected utility from U and D whenever player 2 chooses L and R with equal probability $p = q = 0.5$. Consequently, the only Nash equilibrium exists in mixed strategies for both players randomizing between their available actions with probability $p = q = 0.5$.

Insights: According to Nash equilibrium a player playing multiple games of Matching Pennies against a single opponent should try to randomize his or her actions, while also being sensitive to whether the opponent’s choices follow any sort of predictable pattern. Two types of predictability are of interest here, the first being predictability based on a perceived pattern (e.g., every fifth choice of player 1 is U), the second being predictability based on random processes⁹ with probabilities that deviate from $p = q = 0.5$. Exactly how subjects identify patterns or keep track

⁹Independent and identically distributed.

of shifting probabilities during repeated decisions remains an active question for neuroeconomic inquiry. Interestingly, recent research in monkeys has shown that simple reinforcement learning may be capable of explaining optimal matching pennies behaviors in equilibrium (Lee et al. 2004). More generally, reinforcement learning seems to underlie preference learning and decision in various social and nonsocial contexts, suggesting particular relevance of these models to neuroeconomics (Frank and Claus 2006; Seo and Lee 2012).

2.2.2 *Prisoner's Dilemma*

Extensive and normal form descriptions, as well as the intuition and equilibrium solution to the prisoner's dilemma have been provided in the main text and in Fig. 2.1a, b.

Insights: Few games have been as extensively studied as the Prisoner's Dilemma, yet substantial disagreement remains regarding whether or not humans meaningfully deviate from rational behavior in experimental and real world PD scenarios. Certain seems that in experiments and in real life, human decision-makers cooperate (and avoid the Prisoner's Dilemma outcome) more often than can be explained by mere noisy decision making¹⁰ (Cooper et al. 1996).

Unclear is what kind of cognitive architecture promotes such cooperative behavior. Given the relative simplicity of the Prisoner's Dilemma, explanations that impose cognitive constraints on the decision-makers' ability to identify the expected utility maximizing solution would appear spurious. Instead, human decision-makers appear to systematically compute larger expected utility from cooperative behavior given certain parameterizations of the game.

One interpretation that has been offered for this is that human subjects view even one-shot prisoner's dilemma games as potentially repeated interactions. Once the probability of repeated interaction is increased beyond zero, the space of Nash equilibrium solutions is capable of sustaining any given rate of cooperative behavior, and cooperation becomes explainable within the common framework. This explanation possesses considerable face validity, in the light of experiments involving actual repeated games and the possibility of building reputations, which support the basic idea that humans are responsive to the prospect of repeated interaction and reputation building. The same explanation can be made differently by recourse to decision-makers placing some positive probability of being observed by at least one person with whom they may interact in the future. This makes the idea conceptually very difficult to repudiate (but see Cooper et al. 1996). However, the important question of whether this kind of behavior is supported by a cognitive architecture that supports truly altruistic behavior remains of interest to neuroeconomics. Special interest has been given to one particular way in which such an

¹⁰Economic models exist, which relate such behavior to rational choice under uncertainty (e.g., Neyman 1985; Kreps et al. 1982).

architecture may be expressed, namely in the form of other regarding preferences, or social utility. The importance of other regarding preferences lies in the observation that an ostensible prisoner's dilemma may not always possess the conceptual incentive structure of a prisoner's dilemma to the actual decision-maker. Since one of the avenues for understanding decision-making rests obviously in understanding how incentives and feasibility constraints are represented in the mind of the decision-maker, cooperative behavior (in prisoner's dilemma games and beyond) remains an active area of research in this respect (Fehr and Camerer 2007; Sanfey 2007; Houser and McCabe 2009).

2.2.3 Public Goods Game (with and Without Costly Punishment)

Intuition: The Public Goods Game is an n -person Prisoner's Dilemma (with $n > 2$) in which each person faces the choice between contributing to a shared community pool, or free riding on the contributions of others. Contributions to the pool are multiplied and shared equally among all group members, however, the return to the individual is always smaller than the contribution, so that contributing adds to the overall welfare of the group, but subtracts from the welfare of the individual (Fig. 2.3). Like the

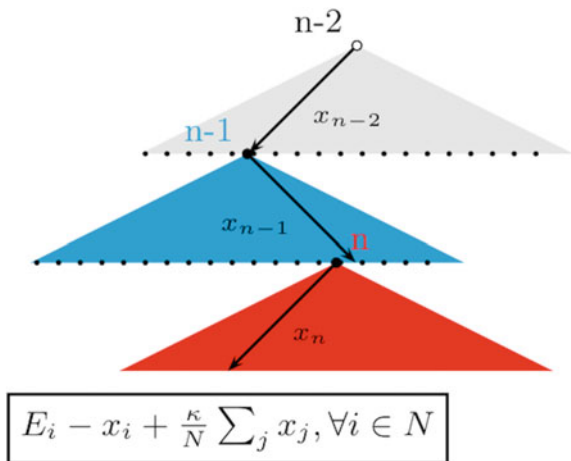


Fig. 2.3 Generic Public Goods Game. *Solid triangles* indicate a player's choice of a continuous value x within some interval. Each player moves without knowledge of what value has been chosen by the other players in game (illustrated by the *dotted lines* along the intervals). For an arbitrary number N players, payoffs are determined as a function of some initial endowment E and a multiplier κ in $[1, N)$. Each player receives exactly their initial endowment less their donation to the public good, x , as well as their share of the κ -multiplied sum of total contributions by the group as a whole

Prisoner's Dilemma, the Public Goods Game is a paragon for games that investigate the emergence of collaboration and altruistic behavior. The game is often played with an added option of costly punishment. In the Public Goods Game with costly punishment, players play a second round during which they may incur a small cost in order to subtract earnings from the final payoffs of other group members.

Equilibrium Solution: In the Public Goods Game, the individual's payoffs are increasing in the contributions made by others, and decreasing in the contributions he or she makes herself. The dominant strategy for the individual is therefore to not contribute. In equilibrium, nobody contributes, and group payoffs are minimized.

In the one-shot game with costly punishment, the same equilibrium solution obtains through backward induction. In the final round, the action of punishing reduces the individual's payoffs (i.e., it is costly), hence no player should ever punish. Consequently, the threat of being punished for free riding should not enter the player's decision in the first round.

Insights: As in the two-person Prisoner's Dilemma actual behavior in experiments and real life often violates the equilibrium prediction for the Public Goods Game. In particular subjects consistently contribute amounts larger than zero to the public good (Chaudhuri 2011). Additionally, subjects frequently punish free riders, even in the one-shot game approximations, and (supposedly anticipating this) humans contribute more in games in which the threat of punishment exists (Fehr and Gächter 2000; Dreber et al. 2008). Interestingly, punishment has also been found to be used against contributors in some experiments (so-called antisocial punishment) (Rand et al. 2011).

As discussed for the Prisoner's Dilemma, a neural architecture promoting cooperative behavior is likely to be sensitive to social outcomes, such as payoff equity, distributive fairness, and reciprocity in behaviors. The Public Goods Game with punishment is especially interesting in this regard, as it indicates player's willingness to pay for a more even, or fair distribution of outcomes. Chapter 5 discusses such punishment behaviors.

Interesting insight comes also from a set of carefully designed behavioral experiments by David Rand and colleagues involving several versions of the Prisoner's Dilemma, including the n -person public goods version (Rand et al. 2012). Across these experiments the authors show cooperation to occur spontaneously under conditions of low reflection and intuitive decision-making. Inducing subjects to reflect consciously on their decisions, on the other hand, reduced cooperative behavior. These data suggest that cooperative behavior may not be entirely explainable by social preferences that promote socially beneficial outcomes, but that such behaviors depend on the mode of cognitive engagement with the decision. To the extent that different networks are involved in these different types of cognitive engagement, these results present important questions for neuroeconomics. Chapter 5 discusses in particular the role of the prefrontal cortex for behaviors involving reciprocal fairness.

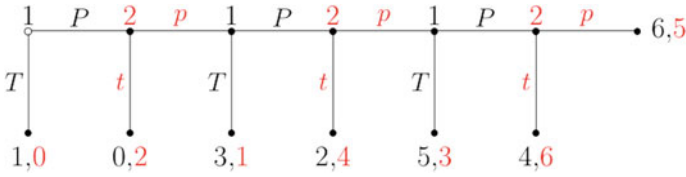


Fig. 2.4 Generic Centipede Game: at each node, the moving player may T(ake) the reward, or P(ass) the move along. Overall rewards increase with each passing decision. Conceptually, each choice of passing costs the passing player 1 utility point, but gains the other player 2 utility points in the depiction shown here

2.2.4 Centipede Game

Intuition: The Centipede Game is a classic example of a group of games that can be solved using backward induction. At its core it describes a finitely often repeated, sequential prisoner's dilemma. In one popular version of the game one or more players take turns deciding whether to take a given monetary reward, or to pass the move on to the next player. Whenever a player decides to take the money, the game ends that round, the taking player receives a large reward and all other players end with smaller or even zero rewards. Whenever the move is passed on, the overall size of the monetary pie grows, and the next player gets to make the decision of taking the money or passing. Critically, if the moving player in round n of the centipede game decides to take the money, then the payoff in round n to the player who passed in round $n - 1$ is smaller than his or her payoff would have been had he or she taken the money in round $n - 1$ instead of passing on the move (Fig. 2.4).

Equilibrium Solution: The dilemma of the centipede game, and games like it, arises because the game is played finitely many rounds, i.e., there will be a final stage in which one player has a strictly dominant choice in taking the money, and the players know this about the game. Using this information, it can be deduced that the last player to move will take the money. This implies that the second to last player may improve his expected utility by not passing on the second to last turn. By extension the third to last mover should not pass on the third to last turn, and eventually this iteration implies that the very first mover should take the money and end the game on the very first turn. This solution is so-called sub-game perfect, meaning that it considers each of the sub-game¹¹ components of the centipede game and identifies a strategy for each player that is an equilibrium strategy for each of the sub-games.

¹¹A sub-game is strictly defined as any subset of a game which has a uniquely identified initial node (i.e., the initial node does not share an information set with any other node), and contains all nodes that follow the initial node in the complete game as well as all successor nodes to these nodes. An additional condition is that all the nodes included in an information set of the sub-game must also be included in the sub-game.

Insights: The Centipede Game is significant to economic theory, because its Nash solution implies a notion of rationality that seems counterintuitive, or even alienating to most human decision-makers (e.g. McKelvey and Palfrey 1992). In fact, the term “Paradox of Backward Induction” has been used to describe the intuition that most decision-makers would prefer passing on earlier moves, and would expect their counterparts to do likewise at earlier positions in the game. In fact, this intuition has fueled rich intellectual debates on the nature of economic rationality, and backward induction in games (e.g., Aumann 1992, 1995; Binmore 1996). For example, it may be deemed rational for a player to have beliefs about his opponents that violate strict economic rationality once this player has been observed to make a move that would be inconsistent with it. In other words, once the first player passes on the first move of the Centipede Game it is not irrational for the second mover to believe that the first mover will pass again on his next move. Consequently, the second mover may prefer passing on her move, given that she may now rationally believe that the first mover will also pass again. Knowing this, it may be rational and strategic for the first mover to initially pass; thus essentially sending a signal to the second mover. Experimental games show that human subjects rarely take the money on the very first round of the Centipede Game (McKelvey and Palfrey 1992).

Actual behavior in the Centipede Game holds numerous insights for neuroeconomists. For one, the backwards induction solution disciplines the way in which a player must iteratively think about the potential outcomes of his actions. Hence, behavior in games that require backward induction may be indicative of the extent of iterated reasoning that a player applies to a decision. Additionally, the notion of rationality we have described indicates the important role of second order beliefs for behavior in the game. That is, it is important for the behavior of player 1, what he thinks that player 2 thinks about the beliefs of player 1. The process of self-referential belief formation and its neural correlates have been investigated by Bhatt and Camerer (2005), and experiments investigating a subject’s depth of reasoning (and the depth of reasoning he or she attributes to others) appear to hold important insights for understanding multi-person strategic interactions (Coricelli and Nagel 2010; De Martino et al. 2013).

2.2.5 *Stag Hunt Game*

Intuition: The Stag Hunt Game is the prototype of the social contract, and a trust dilemma: In *A Discourse on Inequality* written in 1754, Jean-Jacques Rousseau describes a situation in which two individuals go on a hunt, and each of them has to choose one of two possibilities: hunt a hare, which leads to a small personal gain, regardless of the behavior of the other player, or hunt a stag, which leads to a large gain, but will only be successful if both players join forces in doing so. Catching the stag and obtaining the large payoff for both players therefore requires spontaneous cooperation and mutual trust (Fig. 2.5).

		Player 2	
		<i>s</i>	<i>h</i>
Player 1	S	3 3	0 1
	H	1 0	1 1

Fig. 2.5 Generic Stag Hunt. Each player chooses between a hunting a S(tag), or a H(are). Coordinated stag hunts ($\{S, s\}$) generate the highest payoffs for both players. A single stag hunt ($\{S, h\}$ or $\{s, H\}$) does not produce positive utility for the player choosing S(tag). Choosing H(are) always produces an intermediate utility to the player, irrespective of the other player’s action

Equilibrium Solution: The game may look similar to the Prisoner’s Dilemma, in that there are two players that have to choose simultaneously whether to cooperate or not. However, this game does not have a strictly dominant strategy, and possesses two Nash equilibriums in pure strategies (as well as mixed strategy equilibrium): Strategies in which both players always hunt the stag, or always hunt the hare, are both equilibrium solutions to the game. Depending on the actual payoffs used in the game, a mixture can be found, for which the other player will become indifferent to which action they choose, and when both players mix their actions in this way, a mixed strategy equilibrium is reached.¹² The pure strategy equilibriums obtain because hunting the stag is a best response when the other player hunts the stag, and hunting the hare is a best response when the other player hunts the hare. Hunting the stag, which involves social risk taking, however, also constitutes the social optimum, as it gives the higher payoff to both players.

Insights: The Stag Hunt Game allows the investigation of individuals’ attitude toward social risk taking involved in coordinating on mutual trust in the game. This feature of the game is comparable to many social and physical environments in which joint coordination of trusting behavior is required for the attainment of goals. In repeated games, people additionally gain knowledge of other player’s intentions to cooperate through repeated interactions, and applying Theory of Mind (ToM) (Premack and Woodruff 1978) can infer other people’s cognitive states, make predictions on their moves and act consequently. As for the Trust Game (Sect. 2.2.8), having some knowledge about the other player helps to shape one’s strategy: if we know that the other agent is risk-taking, we might predict that he/she

¹²For the values used in the schematic Fig. 2.5, the mixed strategy equilibrium has both players hunting the stag with probability 1/3 and the hare with probability 2/3.

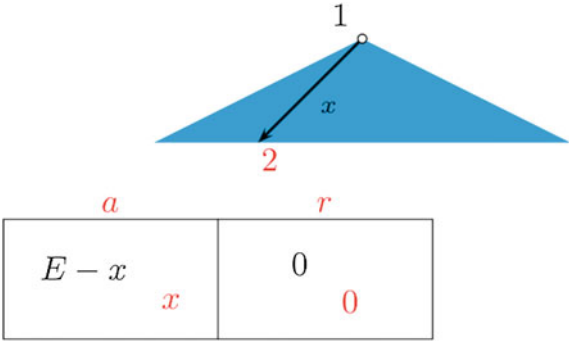


Fig. 2.6 Generic Ultimatum Game (continuous donation). Player 1 is the proposer and chooses some value x along a continuous interval. After proposing x , player two may accept or reject. Acceptance leads to player 1 receiving the remainder of his initial endowment ($E - x$), and player 2 receiving x . If player 2 rejects, both players receive 0

will probably choose to hunt the stag, and we can act consequently. From a neuroscientific perspective, a study from Yoshida et al. (2010) shows that, on one hand, knowledge acquired by updating the beliefs on the other agent through repeated interactions requires the activation of medial prefrontal cortex (the higher the activation the higher the uncertainty of belief inference); on the other hand, choosing a strategy according to the level of sophistication of thinking, meaning how many orders of belief we apply for choosing our strategy, involves the dorso-lateral prefrontal cortex, whose activity positively correlates with the level of sophistication.

2.2.6 *Ultimatum Game*

Intuition: The Ultimatum Game is the classic “take-it-or-leave-it” scenario in game theory. It features two players, the proposer and the responder. The proposer is endowed with an amount of money, e.g., 10 dollars. The proposer moves first, and makes an offer to the responder on how to divide the money; the responder has to accept or reject the offer knowing that, accepting, the money will be divided as the proposer has decided, whereas rejecting neither player will receive anything. For example, if the proposer offers 2 dollars and the responder accepts, the proposer gets 8 dollars and the responder gets 2 dollars; if the responder rejects, they both gets 0. The game is one-shot, meaning the interaction between the two players occurs only once, eliminating the opportunity for reciprocity, and stripping rejections from their potential power of being negotiating tools (Fig. 2.6).

Equilibrium Solution: If the total amount available is x , then the proposer must choose an amount p $[0, x]$ to keep for himself. The responder chooses between two solutions for determining the outcomes: “accept” is equal to $x - p$ for him and to p

for the proposer; “reject” is equal to 0 for both. A strategy profile where the responder accepts an offer if and only if it is larger or equal to $p - x$, and the proposer offers $p - x$, is a Nash equilibrium. If one adopts a more restrictive concept, i.e., the sub-game perfect equilibrium, then equilibrium of this game of perfect information is found by backward induction and is unique, if a zero offer is not allowed. In this equilibrium, the responder accepts any offer, given that getting something is better than getting nothing; the proposer, knowing that, offers the minimum amount.

Insights: A large number of experiments, beginning with Güth et al. (1982), used monetary payments and found behavior substantially different from the offer of a minimal amount by the proposer and acceptance of any positive amount by the responder. It has been repeatedly demonstrated that proposers tend to make fair offers and responders tend to reject offers that are considered to be unfair, such as 1 or 2 dollars out of 10; theories of social preferences have accounted psychological phenomena such as inequity aversion (e.g., Fehr and Schmidt 1999) or negative reciprocity (e.g., Rabin 1993) for the rejections.

The deviation of actual behavior from Rational Choice has opened the discussion on the ultimate psychological and neural mechanism that leads to a rejection. Negative emotions in response to unfairness have been claimed as responsible for the behavior (Pillutla and Murnighan 1996), and evidence in support to this theory has been collected extensively (e.g., Sanfey et al. 2003; Van’t Wout et al. 2006); however, recent findings challenge this account, in that emotional arousal seems to be not necessary in order to trigger rejections (Civai et al. 2010). Moreover, a crucial role is played by expectations, which interact with the unfairness level to influence significantly the rejection rate, as shown by Chang and Sanfey (2013). Overall, the UG, together with Dictator Game (DG), Trust Game (TG) and their manipulations, remains one of the most effective tasks to investigate the cognitive and neural basis of social norm’s compliance.

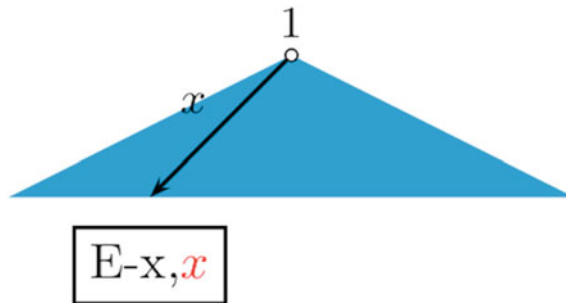


Fig. 2.7 Generic Dictator Game (continuous donation). A degenerate game in which player 1 distributes an initial endowment E between herself and player 2. Player 1 receives $E - x$, while player 2 receives the donated amount x

2.2.7 Dictator Game

Intuition: Forsythe et al. (1994) introduced the Dictator Game (DG), a variant of the UG, which features two players, the dictator and the recipient. The dictator is endowed with an amount of money, e.g., 10 dollars. The dictator is asked to divide his/her endowment with the recipient; the recipient's role is entirely passive, as he/she must accept the offer made by the dictator. For example, if the dictator allocates 2 dollars to the recipient, the dictator gets 8 dollars and the recipient gets 2 dollars. Unlike the UG, in the DG the recipient has no strategic input, and, in this sense, the DG is a degenerate game. This game is useful to investigate the behavior of the UG's proposer when ruling out the strategic thinking, as in the DG the dictator does not have to worry about potential rejections (Fig. 2.7).

Equilibrium Solution: The dictator maximizes his payoffs by keeping the largest amount possible.

Insights: Rational Choice theory predicts that the dictator will offer 0; however, as for the UG, this is not the case in experimental settings. Although the amounts and frequencies of nonzero offers in the DG are less and lower than in the UG, demonstrating that strategic motivations have an effect in the UG, giving behavior in the DG is consistently and significantly larger than zero, and players are often observed to give up to the 50 % of their endowment to the recipient (Forsythe et al. 1994). Interestingly, anonymity and social distance play a very important role in shaping the amount of giving (Hoffman et al. 1994, 1996; Charness and Gneezy 2008): the larger is the degree of anonymity and the social distance, the lower is the average amount of money given by the dictator.

As for the UG, the DG is a useful tool to investigate fairness concerns. In particular, given its peculiar nature of degenerate game, where the recipient has no active role and cannot decide on anything, this game is useful to disentangle actual altruistic motivations from the strategic thinking that may characterize the proposer's offers in the UG. Interestingly, the fact that people still give some money to the recipient opens the discussion about different types of altruism (for a specific discussion, see Chaps. 11 and 12 of this volume).

2.2.8 Trust Game

Intuition: The simple Trust Game (TG) (Berg et al. 1995) features two players, the investor and the trustee. The investor starts with a certain amount X , e.g. 10 dollars, and has to decide how much to keep for him/herself, and how much to give to the trustee. The investor knows that the amount received by the trustee will be triplicated, so that if T is the investment, the trustee receives $3T$. At this point, the trustee must decide how much to return to the investor, from 0 to $3T$. The TG is considered to be an extended DG, as in this case the investment earns a return, and it is widely employed to investigate the issue of trust/social capital (Fig. 2.8).

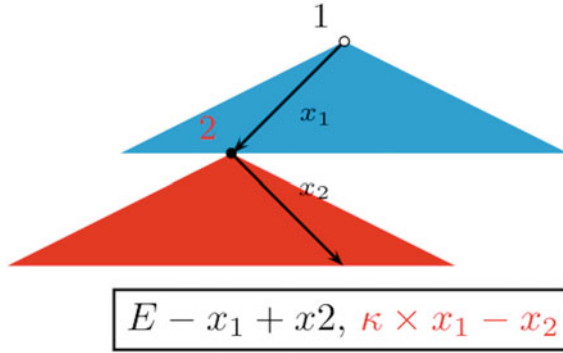


Fig. 2.8 Generic Trust Game (continuous donation): Player 1 entrusts some amount x_1 between 0 and E to player 2. This amount is multiplied by κ , after which player 2 may return some amount x_2 between 0 and κ times x_1 to player 1. Player 1 receives the part of the endowment he kept for himself plus the amount returned by player 2. Player 2 receives the κ —multiplied amount of player 1's initial trust less the amount returned

Equilibrium Solution: Both players are better off with full investment, but the investor has to take the risk in trusting the trustee. In the one-shot version of the game, the sub-game perfect equilibrium would be for the trustee to keep all, wherefore the best response of the investor would be to invest nothing.

Insights: Although Rational Choice predicts the opposite, investors show a surprisingly high amount of blind trust: the average amount invested is half of X . The average amount of return is $1/3$ of $3T$, so that the investor ends up, on average, with T . Cochara et al. (2004) found that investors invest more and trustees return a higher percentage in the finitely repeated trust game with fixed matches (7 rounds) as compared with the one-shot version; in particular, they found two different types of trustee, i.e., those returning $2/3$ of T and those returning 0.

The TG has been widely employed to investigate the psychological and neural underpinnings of trust among strangers; interestingly, it has been possible to show how trust is modulated both by the characteristics of the trustee and by those of the investors. For example, studies manipulating the moral character of the trustee showed that investors were much more likely to make risky investments with “good” partners (e.g., Delgado et al. 2005); on the other hand, it has been shown that administering the neuropeptide oxytocin increases trust in the investor, who is willing to invest more money in the trustee. In particular, Kosfeld et al. (2005) manipulated the nature of the trustee, having a human trustee in one condition and a computer in another, and showed that this increase was not due to a general increase in the willingness to take risks (computer condition), but was specific to the social risks involved in interpersonal interaction (human condition).

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Neuroeconomics

Reuter, M.; Montag, C. (Eds.)

2016, XI, 511 p. 88 illus., 54 illus. in color., Hardcover

ISBN: 978-3-642-35922-4