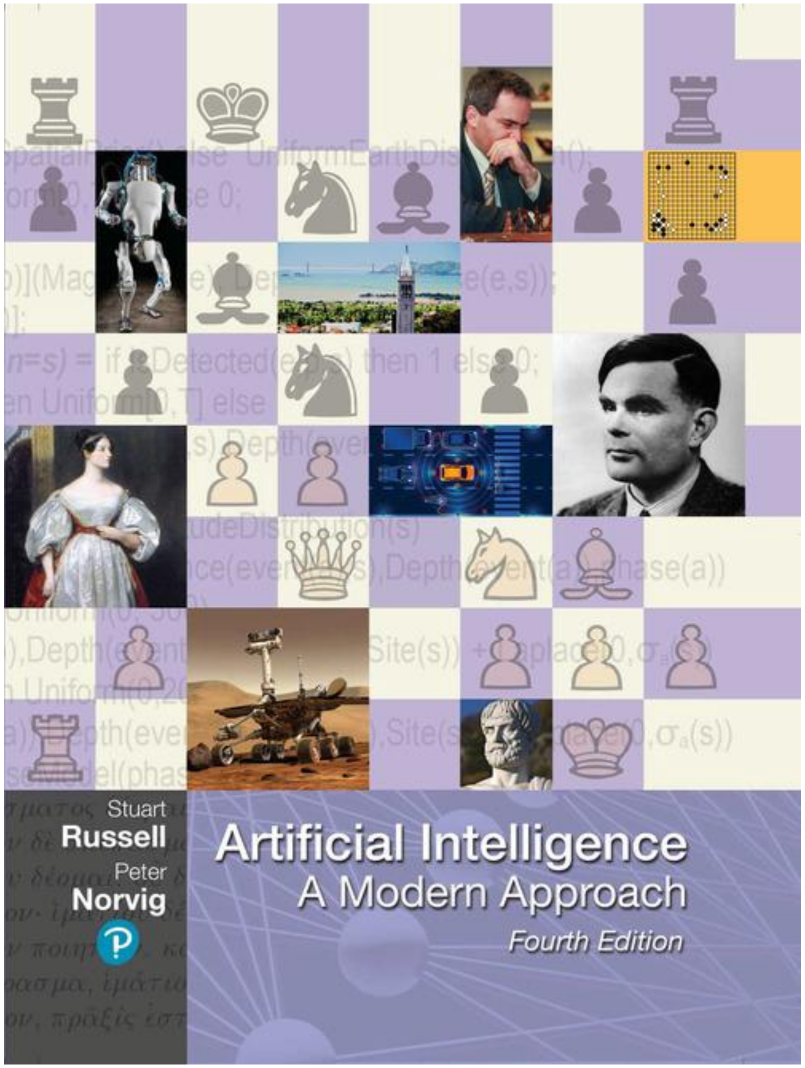
Artificial Intelligence Fundamentals

2024-2025



“We'll show you that you can build a mind from many little parts, each mindless by itself.“

Marvin Minsky, Society of Mind

AIMA Chapter 17

Multiagent Decision Making

Outline

- Properties of Multi-agent Environments
- Non-Cooperative Game Theory
- Cooperative Game Theory
- Making Collective Decisions

Multiagent Environments

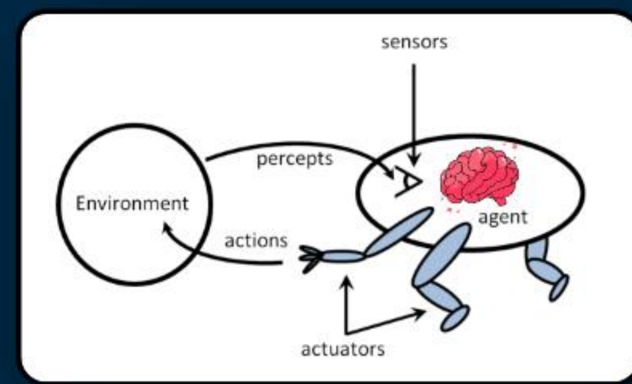
So far, we have largely assumed that **only one agent** has been doing the *sensing*, *planning*, and *acting*.

But this represents a huge simplifying assumption, which fails to capture many real-world AI settings.

In this lecture we will see:

1. **Precise nature** of the multiagent planning problem

2. **The techniques that are appropriate for solving it**—will depend on the relationships among the agents in the environment



AI Agent Architecture
(Russel & Norvig, 1995 - 2022)

Multiagent Systems

Pearson

History of Multiagent AI

It is a curiosity of the field that researchers in AI did not begin to seriously consider the issues surrounding interacting agents until the 1980s:

- the *multiagent systems field* **did not really become established** as a distinctive subdiscipline of AI until a decade later
- In his highly influential *"Society of Mind"* theory, **Marvin Minsky** (1986, 2007) proposed that human minds are constructed from an ensemble of agents. **Doug Lenat** had similar ideas in a framework he called BEINGS (Lenat, 1975).
- **J. Nash** was awarded the Nobel Memorial Prize in Economics (along with Reinhart Selten and John Harsanyi) in 1994 for his work on game theory
- *....still an open research field and arguably one of the main pillars of intelligence!*

Research communities*: Complex Systems, Multi-Agent (Learning) Systems, Parallel / Distributed AI, Federated Learning, Swarm Robotics, …*

Properties of Multiagent Environments

One Decision Maker

- Multiple (logical or physical) actors, it contains only one decision maker
- **Benevolent agent assumption**: agents will simply do what they are told
    - *Special case*: a single decision maker with multiple *effectors* that can operate concurrently (e.g. a human who can *walk* and *talk* at the same time.)
- **Multi-effector planning** manages each effector while handling positive and negative interactions among the effectors.
- **Multi-body planning:** effectors are physically decoupled into detached units

Properties of Multiagent Environments

Multiple Decision Maker

- Multiple actors, multiple decision makers.
- Each have **preferences** and **choose and execute** their own plan
- There are two possibilities:
  - Common goal for the actors, *coordination problem* (same direction)
  - *Own personal preference* and can be diametrically opposed
- **Game theory**: *theory of strategic decision making*
  - Players each taking into account how other players may act
  - Used in **agent design** and **mechanism design**
  - It can be a **cooperative game** where a binding agreement between agents exists enabling robust cooperation.
  - **Non-cooperative game**: no central agreement and no guarantee of cooperation

The use of the word "**game**" here is also not ideal: a natural inference is that game theory is mainly concerned with recreational pursuits, or artificial scenario

Properties of Multiagent Environments

Multiagent planning

- Issue of **concurrency**: plans of each agent may be executed simultaneously
- *Agents must take into account the way in which their own actions interact with the actions of other agents.*

Interleaved execution approach:

- certain the **order of actions** in the respective plans will be preserved
- assume that actions are **atomic**
- must be correct with respect to all possible **interleavings** of the plans
- **does not model** the case where two actions actually **happen at the same time**.
- the number of interleaved sequences is **exponential with the number of agents** and actions rising

Interleaved Actions

For example, suppose we have two agents, A and B, with plans as follows:

$$\begin{aligned} A &: \ [a_1, a_2] \\ B &: \ [b_1, b_2]. \end{aligned}$$

The key idea of the interleaved execution model is that the only thing we can be certain about in the execution of the two agents' plans is that **the order of actions in the respective plans** will be preserved.

If we further assume that **actions are atomic**, then there are six different ways in which the two plans above might be executed concurrently:

$$\begin{gathered} [a_1, a_2, b_1, b_2] \\ [b_1, b_2, a_1, a_2] \\ [a_1, b_1, a_2, b_2] \\ [b_1, a_1, b_2, a_2] \\ [a_1, b_1, b_2, a_2] \\ [b_1, a_1, a_2, b_2] \end{gathered}$$

Properties of Multiagent Environments

True concurrency approach:

- do not attempt to create a full serialized ordering of the actions,
- partially ordered

Perfect synchronization approach

- Global clock,
- Same time, same duration, actions are always simultaneous (*NoOp* allowed).
- simple semantics

Concurrent action constraint:

- actions must or must not be executed concurrently

Concurrent Action Constraint Example

$$
\begin{array}{l}
Actors(A,B)\\
Init(At(A, LeftBaseline) \land At(B, RightNet) \land\\
\qquad Approaching(Ball, RightBaseline) \land Partner(A,B) \land Partner(B,A)\\
Goal(Returned(Ball) \land (At(x, RightNet) \lor At(x, LeftNet))\\
Action(Hit(actor, Ball),\\
\qquad \text{PRECOND:}Approaching(Ball, loc) \land At(actor, loc)\\
\qquad \text{EFFECT:}Returned(Ball))\\
Action(Go(actor, to),\\
\qquad \text{PRECOND:}At(actor, loc) \land to \neq loc,\\
\qquad \text{EFFECT:}At(actor, to) \land \neg At(actor, loc))
\end{array}
$$

Figure 17.1 The doubles tennis problem. Two actors, *A* and *B*, are playing together and can be in one of four locations: *LeftBaseline*, *RightBaseline*, *LeftNet*, and *RightNet*. The ball can be returned only if a player is in the right place. The *NoOp* action is a dummy, which has no effect. Note that each action must include the actor as an argument.

Concurrent Action Constraint Example

$$\text{PLAN 1:} \quad \begin{aligned} A &: [Go(A, RightBaseline), Hit(A, Ball)] \\ B &: [NoOp(B), NoOp(B)]\,. \end{aligned}$$

Problems arise, however, when a plan dictates that both **agents hit the ball at the same time**.

In the real world, this won't work, but the action schema for "Hit" says that the ball will be returned successfully.

The difficulty is that preconditions constrain the state in which an action by itself can be executed successfully, but **do not constrain other concurrent actions** that might mess it up.

Concurrent Action Constraint Example

We solve this problem by augmenting action schemas with one new feature: a **concurrent action constraint** stating which actions must or must not be executed concurrently. For example, the "*Hit*" action could be described as follows:

$$
\begin{aligned}
&Action(Hit(actor, Ball),\\
&\quad \textsc{Concurrent}{:}\forall b \;\; b \neq actor \Rightarrow \neg Hit(b, Ball)\\
&\quad \textsc{Precond}{:}Approaching(Ball, loc) \wedge At(actor, loc)\\
&\quad \textsc{Effect}{:}Returned(Ball))\,.
\end{aligned}
$$

For some actions, the desired effect is achieved only when **another action occurs concurrently**. For example, two agents are needed to carry a cooler full of beverages to the tennis court:

$$
\begin{aligned}
&Action(Carry(actor, cooler, here, there),\\
&\quad \textsc{Concurrent}{:}\exists b \;\; b \neq actor \wedge Carry(b, cooler, here, there)\\
&\quad \textsc{Precond}{:}At(actor, here) \wedge At(cooler, here) \wedge Cooler(cooler)\\
&\quad \textsc{Effect}{:}At(actor, there) \wedge At(cooler, there) \wedge \neg At(actor, here) \wedge \neg At(cooler, here))\,.
\end{aligned}
$$

Cooperation and coordination

Now let us consider a **true multiagent setting** in which *each agent makes its own plan.* Even if the have shared *KB* and *goals*, how can they coordinate to make sure they agree on the plan?

- Adopt **convention** before engaging in joint activity
- **Convention**: constraint on the selection of joint plans
- When conventions are widespread, they are called **social laws**
- Agents can use **communication** to achieve common knowledge of a feasible joint plan (*communication does not necessarily involve a verbal exchange*)
- **Plan recognition:** single action (or short sequence of actions) by one agent is enough for the other to **determine a joint plan** unambiguously
    - E.g. *If agent A heads for the net, then agent B is obliged to go back to the baseline to hit the ball, because plan 2 is the only joint plan that begins with A's heading for the net*).

Non-Cooperative Game Theory

Games with a Single Move: "*Normal Form Games*"

- All players take action simultaneously
- No player has knowledge of the other players' choices
- Defined by 3 components
  - Players
  - Actions
  - *Payoff function*: utility to each player for each combination of actions by all the players (*payoff matrix*)

Example. *Two-finger Morra game*, two players, O and E, simultaneously display one or two fingers. Let the total number of fingers displayed be f. If f is odd, O collects f dollars from E; and if f is even, E collects f dollars from O.[1] The payoff matrix for two-finger Morra is as follows:

	O: *one*	O: *two*
E: *one*	$E = +2, O = -2$	$E = -3, O = +3$
E: *two*	$E = -3, O = +3$	$E = +4, O = -4$

Non-Cooperative Game Theory

Games with a single move: "Normal form games"

Why game-theoretic ideas are needed at all?

Why can't we tackle the challenge facing (say) player E using the apparatus of *decision theory* and *utility maximization* that we've been using in prev. lectures?

To choose optimally between these possibilities, "E" must take into account how "O" ***will act as a rational decision maker***. But "O", in turn, should take into account the fact that "E" ***is a rational decision maker***.

Thus, decision making in multiagent settings is quite different in character to decision making in *single-agent settings*, because the **players need to take each other's reasoning into account**.

Non-Cooperative Game Theory

Games with a single move: Normal form games

- The role of "solution concepts" in *game theory* is to try to make reasoning precise
- **A pure strategy** is a deterministic policy; for a single-move game, a pure strategy is just a single action.
- **Mixed strategy**: a randomized policy that selects actions according to a probability distribution.
- A **strategy profile** is an assignment of a strategy to each player

	Ali:testify	*Ali:refuse*
Bo:testify	$A = -5, B = -5$	$A = -10, B = 0$
Bo:refuse	$A = 0, B = -10$	$A = -1, B = -1$

most famous game in the game theory —**the prisoner's dilemma**

Non-Cooperative Game Theory

	Ali:testify	*Ali:refuse*
Bo:testify	$A = -5, B = -5$	$A = -10, B = 0$
Bo:refuse	$A = 0, B = -10$	$A = -1, B = -1$

Suppose “Bo” plays testify. “Ali” gets 5 years if “Ali” testify and 10 years if “Ali” don’t, so in that case testifying is better.

On the other hand, if “Bo” plays refuse, then “Ali” go free if “Ali” testify and “Ali” get 1 year if “Ali” refuse, so testifying is also better in that case.

So, no matter what “Bo” chooses to do, it would be better for “Ali” to testify.

Ali has discovered that testify is **a dominant strategy** for the game

Non-Cooperative Game Theory

- s for player p **strongly dominates** strategy s' if the outcome for s is better for p than the outcome for s', **for every choice of strategies** by the other player(s).
- Strategy s **weakly dominates** s' if s is better than s' on at least **one strategy profile** and **no worse** on any other.
- A **dominant strategy** is a strategy that dominates all others.
- Rational player will always choose a *dominant strategy* and avoid a dominated strategy.
- Where all players choose a *dominant strategy*, then the outcome that results is said to be a **dominant strategy equilibrium**

Nash Equilibrium

A *strategy profile* is a "Nash equilibrium" if no player could unilaterally change their strategy and as a consequence receive *a higher payoff*, under the assumption that the other players stayed with their strategy choices.

- **weaker than dominant strategy equilibrium**, but Nash equilibrium it is much more widely applicable

In a Nash equilibrium, every player is simultaneously playing a **best response** to the choices of their counterparts.

A Nash equilibrium represents a **stable point in a game**: stable in the sense that *there is no rational incentive for any player to deviate*.

However, Nash equilibria are **local stable points**: as we will see, a game may contain multiple Nash equilibria.

Nash Equilibrium

It is easy to verify that there are no dominant strategies in this game, for either player, and hence no ***dominant strategy equilibrium***.

	$Ali{:}l$	$Ali{:}r$
$Bo{:}t$	$A = 10, B = 10$	$A = 0, B = 0$
$Bo{:}b$	$A = 0, B = 0$	$A = 1, B = 1$

However, the strategy profiles (t,l) and (b,r) are both *Nash equilibria*.

It is in the interests of both agents to aim for the same Nash equilibrium—either (t, l) or (b, r)—but since we are in the domain of non-cooperative game theory, players must make their choices independently, without any knowledge of the choices of the others, and without any way of making an agreement with them.

- **coordination problem**: the players want to coordinate their actions globally, so that they both choose actions leading to the same equilibrium, but must do so using only local decision making.

Social Welfare

- Want to choose the best overall outcome—the outcome that would be best "for society as a whole"
- Main idea: *Avoid outcomes that waste utility*
- **Pareto optimality**: there is no other outcome that would make one player better off without making someone else worse off (from *Vilfredo Pareto*, an Italian economist)
  - If you choose an outcome that is not Pareto optimal, it wastes utility in the sense that you could have given more utility to at least one agent, without taking any from other agents
- **Utilitarian social welfare** is a measure of how good an outcome is in the aggregate
- **Egalitarian social welfare**: maximize expected utility of the worst-off member of society
- **Gini coefficient**, which summarizes how evenly utility is spread among the players.

Social Welfare

Applying these concepts to the **prisoner's dilemma game**, explains **why** it is called a *dilemma*.

Recall that (testify, testify) is a *dominant strategy equilibrium*, and the only *Nash equilibrium*.

However, this is the only outcome that is not Pareto optimal. The outcome (refuse, refuse) maximizes both **utilitarian** and **egalitarian** social welfare.

The dilemma in the prisoner's dilemma thus arises because a very strong solution concept (dominant strategy equilibrium) leads to an outcome that essentially fails every test of what counts as a "reasonable outcome" from the point of view of the "*society*."

Yet **there is no clear way for the individual players to arrive at a better solution.**

Social Welfare

Computing equilibria

If players have only a finite number of possible choices, then **exhaustive search** can be used to find equilibria:

1. iterate through each possible strategy profile
2. check whether any player has a beneficial deviation from that profile;
3. if not, then it is a Nash equilibrium in pure strategies.

Dominant strategies and *dominant strategy equilibria* can be computed by similar algorithms.

Unfortunately, the number of possible strategy profiles for n players each with m possible actions, is m^n, i.e., infeasibly large for an exhaustive search.

Social Welfare

Computing equilibria

Myopic best response (or "iterated best response")

1. Start by choosing a strategy profile at random; then,

2. If some player is not playing their optimal choice given the choices of others, flip their choice to an optimal one, and repeat the process

3. The process will converge if it leads to a strategy profile in which every player is making an optimal choice, given the choices of the others—a Nash equilibrium

For **two players, Zero-sum games** (games in which the payoffs always add up to zero) -> **Maximin technique**

- **Minimax** algorithm
- once the first player has revealed a strategy, the second player might as well choose a pure strategy

Pearson

Cooperative Game Theory

Cooperative games capture decision making scenarios in which agents can form **binding agreements with one another to cooperate**.

They can then benefit from **receiving extra value compared to what they would get by acting alone**.

Cooperative games with transferable utility

- The idea of the model is that when a group of agents cooperate, the group as a whole obtains some utility value, which can then be split among the group members.
- The model does not say what actions the agents will take, nor does the game structure itself specify how the value obtained will be split up (that will come later).

Cooperative Game Theory

$G = (N, v)$ to say that a cooperative game, G, is defined set of players $N = \{1,\ldots,n\}$ and a characteristic function, v, which computes the value every subset of players could obtain if they cooperate.

Coalition: subset of players *C*.

- The set of all players *N* is known as **the grand coalition**.
- Choice of joining one coalition creates partitions.
- *players N* is a set of coalitions $\{C_1, . . . , C_k\}$

$$C_i \neq \{\,\}$$
$$C_i \subseteq N$$
$$C_i \cap C_j = \{\,\} \text{ for all } i \neq j \in N$$
$$C_1 \cup \cdots \cup C_k = N\,.$$

For example, if we have $N = \{1, 2, 3\}$, then there are seven possible coalitions:

$\{1\}, \{2\}, \{3\}, \{1, 2\}, \{2, 3\}, \{3, 1\}$, and $\{1, 2, 3\}$

and five possible coalition structures:

$\{\{1\},\{2\},\{3\}\}, \{\{1\},\{2, 3\}\}, \{\{2\},\{1, 3\}\}, \{\{3\},\{1, 2\}\}$, and $\{\{1, 2, 3\}\}$.

Cooperative Game Theory

The payoff must satisfy the constraint that each coalition C splits up all of its value $v(C)$ among its members:

$$\sum_{i \in C} x_i = v(C) \qquad \text{for all } C \in CS$$

Superadditivity: Some cooperative games have two coalitions merge together

$$v(C \cup D) \geq v(C) + v(D) \qquad \text{for all } C, D \subseteq N$$

An **imputation** for a cooperative game (N, v) is a **payoff vector** that satisfies

$$\sum_{i=1}^{n} x_i = v(N)$$
$$x_i \geq v(\{i\}) \text{ for all } i \in N\,.$$

Shapley value: "fair" distributions scheme

- divide the $v(N)$ value among the players, given that the grand coalition N formed
- Divided according to **contribution** creating the value v(N).

Cooperative Game Theory

Marginal contribution that player i makes to C is denoted by $mc_i(C)$:

$$mc_i(C) = \nu(C \cup \{i\}) - \nu(C).$$

Fairness axioms satisfied by the *Shapley value*:

- *Efficiency*: $\sum_{i \in N} \phi_i(G) = \nu(N)$. (All the value should be distributed.)
- *Dummy Player*: If i is a dummy player in G then $\phi_i(G) = 0$. (Players who never contribute anything should never receive anything.)
- *Symmetry*: If i and j are symmetric in G then $\phi_i(G) = \phi_j(G)$. (Players who make identical contributions should receive identical payoffs.)
- *Additivity*: The value is additive over games: For all games $G = (N, \nu)$ and $G' = (N, \nu')$, and for all players $i \in N$, we have $\phi_i(G + G') = \phi_i(G) + \phi_i(G')$.

Making Collective Decisions

Mechanism design—the problem of designing the right game for a collection of agents to play.

Formally, a mechanism consists of:

1. **A language** for describing the set of allowable strategies that agents may adopt.

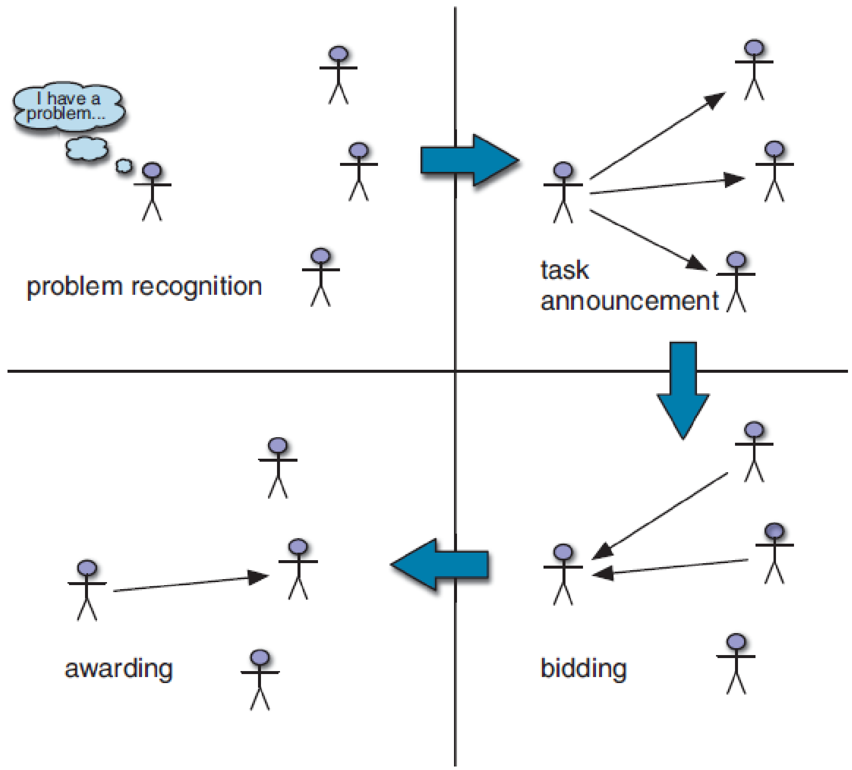
2. **A distinguished agent**, called *the center*, that collects reports of strategy choices from the agents in the game. (For example, the auctioneer is the center in an auction.)

3. **An outcome rule**, known to all agents, that the center uses to determine the payoffs to each agent, given their strategy choices. This section discusses some of the most important mechanisms.

Making Collective Decisions

Allocating tasks with the “*contract net*” has four phases

One of the most widely implemented and best-studied frameworks for cooperative problem solving



The contract net task allocation protocol.

Making Collective Decisions

Allocating scarce resources with auctions

Ascending-bid auction or English auction:

- asking for a minimum (or reserve) bid b_{min} .
- $b_{min} + d$, for some increment d,
- auction ends when nobody is willing to bid, last bidder wins
- Dominant strategy

Sealed-bid auction

- Each bidder makes a single bid and communicates it to the auctioneer, without the other bidders seeing it.

Sealed-bid second-price (aka "Vickrey auction")

- Winner pays second highest bid rather than own.
- Because of its simplicity and the minimal computation requirements for both seller and bidders, the Vickrey auction is widely used in distributed AI systems.

Making Collective Decisions

Voting

- Studied in *"social choice theory"*

- Using a social welfare function, to come up with a **social preference order**: a ranking of the candidates, from most preferred down to least preferred.

- **4 properties** of *good social welfare* function to satisfy:

    - The **Pareto Condition**: simply says that if every voter ranks ω_i above ω_j , then $\omega_i \succ^* \omega_j$
    - The **Condorcet Winner Condition**: Condorcet winner is a candidate that would beat every other candidate in a *pairwise election*. if ωi is a Condorcet winner, she should be ranked first.
    - **Independence of Irrelevant Alternatives** (IIA): voter preferences are such that $\omega_i \succ^* \omega_j$. one voter changed prefs, but *not about the relative ranking* of ωi and ωj. Then $\omega_i \succ^* \omega_j$ should not change.
    - **No Dictatorships**

Arrow's theorem says impossible to satisfy all four conditions

Making Collective Decisions

The Zeuthen strategy

How negotiation participants should behave when using the monotonic concession protocol for task-oriented domains?

- 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

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

Higher risk value indicate that i has less to lose from conflict, and so is more willing to risk conflict.

Nashpy: a Python library used for equilibria computation

Tutorial: building and finding the equilibrium for a game

Introduction to game theory

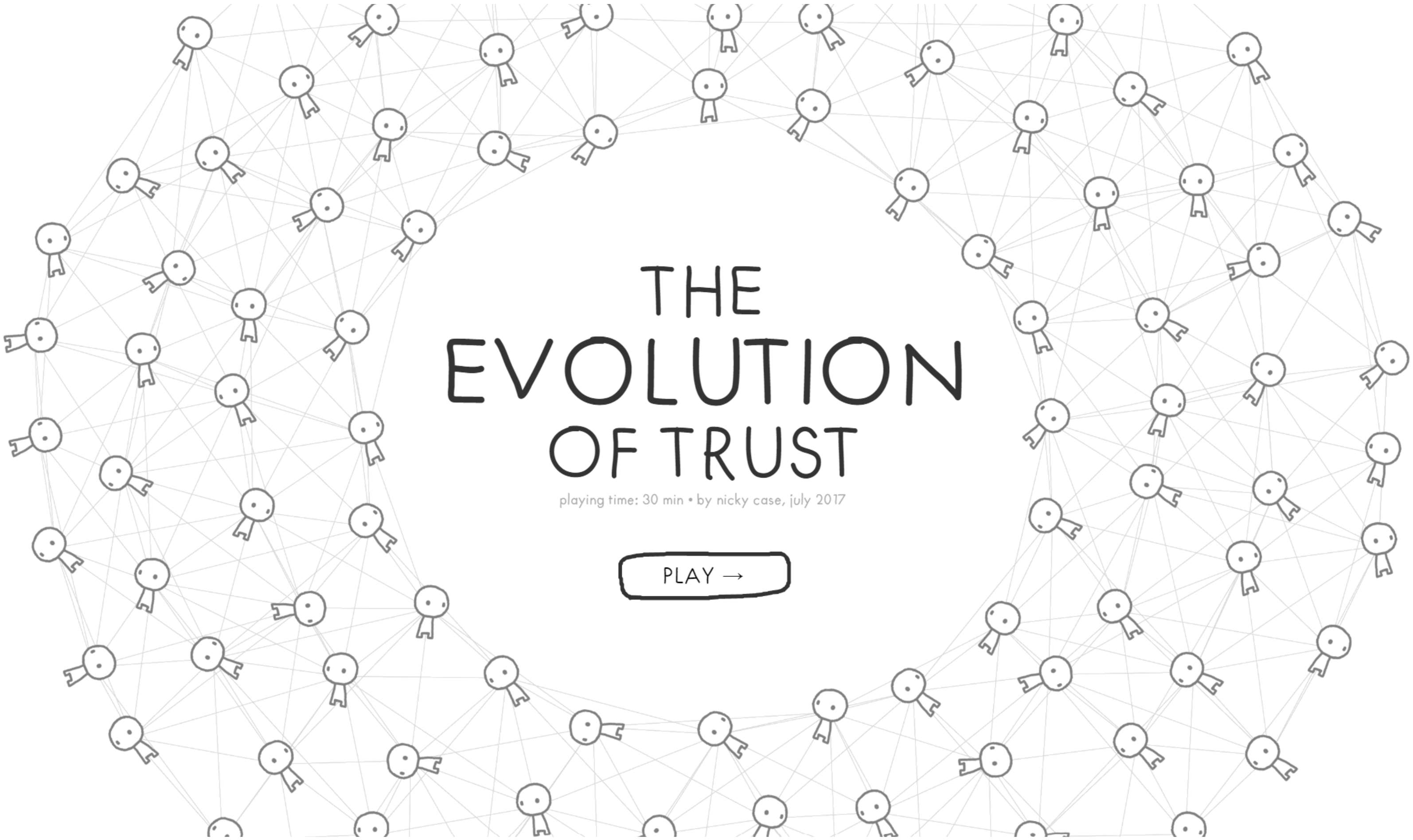
Game theory is the study of strategic interactions between rational agents. This means that it is the study of interactions when the involved parties try and do what is best from their point of view.

As an example let us consider Rock Paper Scissors. This is a common game where two players choose one of 3 options (in game theory we call these *strategies*):

- Rock
- Paper
- Scissors

1. https://nashpy.readthedocs.io/en/stable/tutorial/index.html
2. Game Theory concepts with application in Python using Nashpy (Part 1) | by Mythili Krishnan

The Evolution of Trust



The Evolution of Trust – by Nicky Case, 2017

Summary

Multiagent planning is necessary when there are other agents in the environment with which to **cooperate** or **compete**.

Game theory describes rational behavior for agents in situations in which multiple agents interact.

"Solution concepts" in game theory are intended to characterize rational outcomes of a game

Non-cooperative game theory assumes that agents must make their decisions independently

Cooperative game theory considers settings in which agents can make binding agreements to form coalitions in order to cooperate

In the next lecture…

- The Limits of AI
- Can Machines Really Think?
- The Ethics of AI
- Future AI
    - AI Components
    - AI Architectures