

Designing Agent Organisations using a Role Algebra

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ABSTRACT

Multi-agent systems can be viewed as organisations of individual agents. Designing an agent organisation is a complex process involving defining the structural relationships among agents, the lines of inter-agent communication, and the agent functionality. Existing approaches to agent organisation design are difficult to apply in practice since they require the human designer to take design decisions while working at a low level of abstraction.

This paper aims at contributing to semi-automating the agent organisation design process. Towards this aim, a role algebra capturing a number of basic relations among roles is formally defined and its semantics are described based on a two-sorted algebra.

The use of the role algebra is demonstrated by an example from a telephone repair service teams case study

Keywords

Software Agents, Multi-Agent Systems, Agent-Oriented Software Engineering

1. INTRODUCTION

Multi-agent system architectures can be naturally viewed as organised societies of individual computational entities e.g. [4, 12, 16], and hence the problem of designing a multi-agent system refers to designing an *agent organisation*¹. The criteria affecting an agent organisation design decision are numerous and highly dependent on factors that may change dynamically. Therefore, there is no standard best organisation for all circumstances [11, 12]. As a result, agent organisation design rules are left vague and informal, and their application is mainly based on the creativity and the intuition of the human designer. This can be a serious drawback when designing large and complex real-world agent systems. Therefore, many authors argue that social and organisational abstractions should be considered as first class design constructs and that the agent system designer should reason at a high abstraction level, e.g. [6, 9].

¹ In this paper the terms *multi-agent system* and *agent organisation* are used interchangeably.

In this paper we propose an approach providing semi-automatic support for the high-level design of agent organisations. It uses role models as basic building blocks, and formalises the rules and constraints of their combination in a role algebra. This enables semi-automatic tool support for the agent organisation designer. The approach has been incorporated in an experimental version of the Zeus agent building toolkit [8].

The rest of this paper is structured as follows: in the next section some deficiencies in the current methodologies for agent-oriented software engineering are highlighted, and an overview of a semi-automatic approach to role-based agent organisation design is given. Subsequently, role characteristics and possible relations among roles are discussed in the light of examples. In the next step a formal model of role relations, the *role algebra*, is defined and its semantics is discussed using a two-sorted algebra. The use of the role algebra to design an agent organisation is illustrated by an example based on a case study about telephone repair service teams. Finally, directions for future work are presented.

2. DESIGNING AGENT ORGANISATIONS

Early research prototypes of agent-based systems were built in an ad-hoc manner. However, the need to engineer agent systems solving real-world problems has given rise to a number of systematic methodologies for agent oriented analysis and design such as MESSAGE [3], GAIA [16] and SODA [9]. All these methodologies involve a number of analysis and design sub-models emphasising particular analysis and design aspects.

2.1 Weaknesses of Agent Organisation Design Approaches

Existing approaches to designing agent systems could be further improved in the following ways:

- A more systematic way to construct large agent system design models from the analysis models. The steps involved in transforming analysis to design models are not specified to a detail that enables at least some

degree of automation by a software tool [13].

- By considering non-functional requirements on design time. The aim should be to achieve as optimum organisation on design time as possible. To achieve this, some means for considering non-functional requirements before actually deploying the multi-agent system is needed. This hypothesis is along the lines of similar works [10, 11] where the behaviour of a multi-agent system is modelled and studied before actual system deployment.
- By reusing organisational settings. This view regarding reuse of organisational settings has been inspired by the concepts introduced in [18]. It is believed that that work can be further extended by classifying known organisational patterns, and by providing some rigorous means for selecting them in a particular design context.

2.2 Background

Existing role-based approaches to multi-agent system design stress the need to identify and characterise relations between roles [1, 6]. However, only a small number of approaches investigate the consequences of role relations on the design of multi-agent systems, e.g. [6]. This is partly due to lack of formal foundations of role relationships. Therefore, in this work we first identified role relations that would affect multi-agent system design and subsequently we formalised them in an algebraic specification model. Role identification was based on organisational principles and in particular on *role theory* [2].

Role theory emphasises that various relations may exist between roles. For example, an examiner cannot also be a candidate at the same time and therefore appointing these roles to a person at the same time results to inconsistency. Role relations can be complex. For example, a university staff member who is also a private consultant may have conflicting interests. In this case, appointing these roles to the same person is possible but it would require appropriate mechanisms to resolve the conflicting behaviour.

This paper describes part of a work where an attempt to extract role relations from human organisations with an eye on using them to specify agent behaviour has been made. The reason for searching for role relations in the human organisations domain was that agent research traditionally aimed to develop agents that mimic human behaviour and can be organised in a manner similar to humans. As roles have been extensively used in human business organisations, e.g. [17], it was natural to examine human organisations to identify role relations.

2.3 Role Characteristics

Following [6], a role is defined as associated with a *position* and a set of *characteristics*. Each characteristic

includes a set of *attributes*. Countable attributes may further take a range of values. More specifically, a role is capable of carrying out certain *tasks* and can have various *responsibilities* or *goals* that aims to achieve. Roles normally need to interact with other roles, which are their *collaborators*. Interaction takes place by exchanging messages according to *interaction protocols*. A collection of interacting roles representing collective behaviour constitutes a *role model*.

Roles can be extended to create specialised roles by a process called role *specialisation* or *refinement* [1, 6]. Specialised roles represent additional behaviour on top of the original role behaviour in a manner similar to inheritance in object-oriented systems.

In order for roles to pragmatically represent behaviour in an application domain, they need to model issues relevant to non-functional requirements in that domain. Therefore, the above role definition is extended to include *performance variables*. Performance variables are parameters whose value defines the run-time behaviour represented by a role. For example, if the behaviour a role represents requires using some resource like storage space, the resource capacity can be modelled by a performance variable. Performance variables can also be defined at an agent level. In that case, their value is a function of the function of the respective performance variables of all roles the agent is capable of playing. This allows us to apply design heuristics by imposing constraints on the values of the agent performance variables that must be observed when allocating roles to agents. This is illustrated in the example given in section 4.

3. A ROLE ALGEBRA FOR AGENT SYSTEM DESIGN

Based on role theory [2] and on case studies of human activity systems, e.g. [14], six basic role relations have been identified. In this section, a formal model of role relations is defined, referred by the term *role algebra*. Using relations from the role algebra, constraints driving the assignment of roles to agents can be specified and hence the agent organisation design process can be partially automated.

3.1 Relations of the Role Algebra

Let R be a set of roles. For any $r_1, r_2 \in R$, the following binary relationships may hold:

1) **Equals (eq)** — This means that r_1 and r_2 describe exactly the same behaviour. For example, the terms *Advisor* and *Supervisor* can be used to refer to people supervising PhD students. When two roles are equal, an agent playing the one role also plays the other at the same time. The relation $Equals \subseteq R \times R$ is an equivalence relation since it is reflexive, symmetric and transitive:

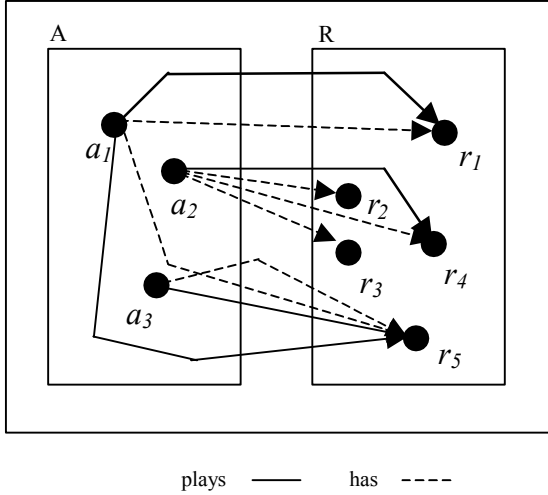


Figure 1: Semantics of role relations

- a) $\forall r : R (r \text{ eq } r)$
 - b) $\forall (r_1, r_2) : R \times R (r_1 \text{ eq } r_2 \Rightarrow r_2 \text{ eq } r_1)$
 - c) $\forall (r_1, r_2, r_3) : R \times R \times R ((r_1 \text{ eq } r_2) \wedge (r_2 \text{ eq } r_3) \Rightarrow (r_1 \text{ eq } r_3))$
- 2) **Excludes (not)** — This means that r_1 and r_2 cannot be assigned to the same agent simultaneously. For example, in a conference reviewing agent system, an agent should not be playing the roles of paper author and paper reviewer at the same time. Furthermore, a role cannot exclude itself — if it would then no agent would ever play it. Therefore, the relation $Excludes \subseteq R \times R$ is anti-reflexive and symmetric:
- a) $\forall r : R (\neg(r \text{ not } r))$
 - b) $\forall (r_1, r_2) : R \times R (r_1 \text{ not } r_2 \Rightarrow r_2 \text{ not } r_1)$
- 3) **Contains (in)** — This means that a role is a sub-case/specialisation of another role. Therefore, the behaviour the first role represents completely includes the behaviour of the second role. For example, a role representing *Manager* behaviour completely contains the behaviour of the *Employee* role. When two roles such that the first contains the second are composed, the resulting role contains the characteristics of the first role only. Therefore, the relation $Contains \subseteq R \times R$ is reflexive and transitive:
- a) $\forall r : R (r \text{ in } r)$
 - b) $\forall (r_1, r_2, r_3) : R \times R \times R ((r_1 \text{ in } r_2) \wedge (r_2 \text{ in } r_3) \Rightarrow (r_1 \text{ in } r_3))$
- 4) **Requires (and)** — The *Requires* relation can be used to describe that when an agent is assigned a particular role,

then it must also be assigned some other specific role as well. This is particularly applicable in cases where agents need to conform to general rules or play organisational roles. For example, in a university application context, in order for an agent to be a *Library_Borrower* it must be a *University_Member* as well. Although the behaviour of a *Library_Borrower* could be modelled as part of the behaviour of a *University_Member*, this would not be convenient since this behaviour could not be reused in other application domains where being a *Library_Borrower* is possible for everyone. Furthermore, each role requires itself. Intuitively, the roles that some role r requires are also required by all other roles that require r . Therefore, the relation $Requires \subseteq R \times R$ is reflexive, and transitive:

- a) $\forall r : R (r \text{ and } r)$
- b) $\forall (r_1, r_2, r_3) : R \times R \times R ((r_1 \text{ and } r_2) \wedge (r_2 \text{ and } r_3) \Rightarrow (r_1 \text{ and } r_3))$

5) **Addswith (add)** — The *Addswith* relation can be used to express that the behaviours two roles represent do not interfere in any way. For example, the *Student* and the *Football_Player* roles describe non-excluding and non-overlapping behaviours. Hence, these roles can be assigned to the same agent without any problems. The relation $Addswith \subseteq R \times R$ is reflexive and symmetric:

- a) $\forall r : R (r \text{ add } r)$
- b) $\forall (r_1, r_2) : R \times R ((r_1 \text{ add } r_2) \Rightarrow (r_2 \text{ add } r_1))$

6) **Mergewith (merge)** — The *Mergewith* relation can be used to express that the behaviours of two roles overlap to some extent or that different behaviour occurs when two roles are put together. For example, a *Student* can also be a *Staff_Member*. This refers to cases when PhD students start teaching before they complete their PhD or they register for another degree (e.g. an MBA) after their graduation. Although members of staff, these persons cannot access certain information (e.g. future exam papers) due to their student status. Also, their salaries are different. In cases like this, although the two roles can be assigned to the same agent, the characteristics of the composed role are not exactly the characteristics of the two individual roles put together. The relation $Mergewith \subseteq R \times R$ is symmetric:

- a) $\forall (r_1, r_2) : R \times R (r_1 \text{ merge } r_2 \Rightarrow r_2 \text{ merge } r_1)$

3.2 Semantics of Role Relations

To describe the semantics of role relations we represent an agent organization by a two-sorted algebra (fig. 1). The algebra includes two sorts, A representing agents and R representing roles.

Let $Has : A \rightarrow R$ be a relation mapping agents to roles. The term “has” means that a role has been allocated to an agent by some role allocation procedure or tool. It is possible for

an agent to have roles that do not contribute to defining the agent behaviour. For example, this happens when roles merge with other roles. For each $a \in A$, let $a.has$ be the set of roles that the agent a maps to in the relation Has . In other words, $a.has$ denotes the relational image of the singleton $\{a\} \subseteq A$ in the relation Has .

Let $Plays: A \rightarrow R$ be a relation mapping agents to roles again. The term “plays” means that that the behaviour a role represents is actively demonstrated by the agent, for example the role does not merge with other roles that are also played by the agent. For each $a \in A$, let $a.plays$ denote the set of roles that the agent a maps to in the relation $Plays$. In other words, $a.plays$ denotes the relational image of the singleton $\{a\} \subseteq A$ to the relation $Plays$.

The meaning of the relations between roles introduced in section 3.1 can now be described as follows:

- **Equals** — An agent has and plays equal roles at the same time.

$$\forall a : A, (r_1, r_2) : R \times R \cdot (r_1 \text{ eq } r_2 \Leftrightarrow ((r_1 \in a.has \Leftrightarrow r_2 \in a.has) \wedge (r_1 \in a.plays \Leftrightarrow r_2 \in a.plays)))$$

- **Excludes** — Excluded roles cannot be assigned to the same agent.

$$\forall a : A, (r_1, r_2) : R \times R \cdot (r_1 \text{ not } r_2 \Leftrightarrow \neg(r_1 \in a.has \wedge r_2 \in a.has))$$

- **Contains** — Contained roles must be assigned and played by the same agent as their containers.

$$\forall a : A, (r_1, r_2) : R \times R \cdot (r_1 \text{ in } r_2 \Leftrightarrow ((r_2 \in a.has \Rightarrow r_1 \in a.has) \wedge (r_2 \in a.plays \Rightarrow r_1 \in a.plays)))$$

- **Requires** — Required roles must be played by the same agent as the roles that require them.

$$\forall a : A, (r_1, r_2) : R \times R \cdot (r_1 \text{ and } r_2 \Leftrightarrow (r_1 \in a.plays \Rightarrow r_2 \in a.plays))$$

- **MergesWith** — When two roles merge, only the unique role that results from their merge is played by an agent.

$$\forall a : A, (r_1, r_2) : R \times R \cdot (r_1 \text{ merge } r_2 \Leftrightarrow \exists! r_3 : R \cdot ((r_1 \in a.has \wedge r_2 \in a.has) \Rightarrow (r_1 \notin a.plays \wedge r_2 \notin a.plays \wedge r_3 \in a.has)))$$

For example, let us assume that roles r_2 and r_3 merge resulting to role r_4 . Based on the above semantic definition, if an agent has r_2 and r_3 then it must also have r_4 and it must not play r_2 and r_3 (the agent may or may not play r_4 depending on the relations of r_4 with the other roles the agent has). The example of a Mergeswith relation between roles r_2 , r_3 , and r_4 , where r_4 is played by the agent, is depicted in fig. 1.

- **AddsWith** — There is no constraint in having or playing roles that add together.

$$\forall a : A, (r_1, r_2) : R \times R \cdot (r_1 \text{ add } r_2 \Leftrightarrow (r_1 \in a.has \Rightarrow ((r_2 \in a.has \vee r_2 \notin a.has) \wedge (r_2 \in a.plays \vee r_2 \notin a.plays))))$$

Using the above semantic axioms, it is trivial to verify that the properties of role relations introduced in section 3.1 hold.

Furthermore, relations between more than two roles can be defined in a similar manner. In that case, a predicate notation is more convenient to represent role relations. For example, when three roles r_1 , r_2 , and r_3 merge to r_4 this can be noted by $\text{merge}(r_1, r_2, r_3, r_4)$. In this paper, we will not provide any formal definitions for relations among roles with arity greater than two.

Role relations, as defined in the above algebra, constrain the way that roles can be allocated to agents. Therefore, the agent organisation design problem is transformed to a constraint satisfaction problem that must be solved for roles to be allocated to agents. The problem can be constrained further by including constraints based on general design heuristics. These constraints are expressed on the performance variables of the agents. For example, the system designer should be able to define the maximum number of roles that an agent could play, or an upper limit to the resource capacity that the roles an agent plays would require. Furthermore, role allocation heuristics could also be specified. For example, roles requiring access to similar resources could be required to be assigned to the same agent.

4. EXAMPLE: SUPPORTING MOBILE WORK TEAMS

For this example we consider a case study concerning telephone repair service teams. The aim is to build an agent system that would assist field engineers to carry out their work. Among the issues involved in such a system are those of travel management, teamwork coordination, and expertise knowledge management [14, 15].

Travel management is about support to mobile workers for moving from one repair task location to another. It involves finding the position of each worker, obtaining relevant travel information, planning the route to the next repair task location and allocating travel resources as required. Teamwork coordination is about allocating and coordinating the execution of repair tasks in a decentralised manner taking into account the personal preferences and working practices of the mobile workers. Work knowledge management concerns storage and dissemination of expertise work knowledge.

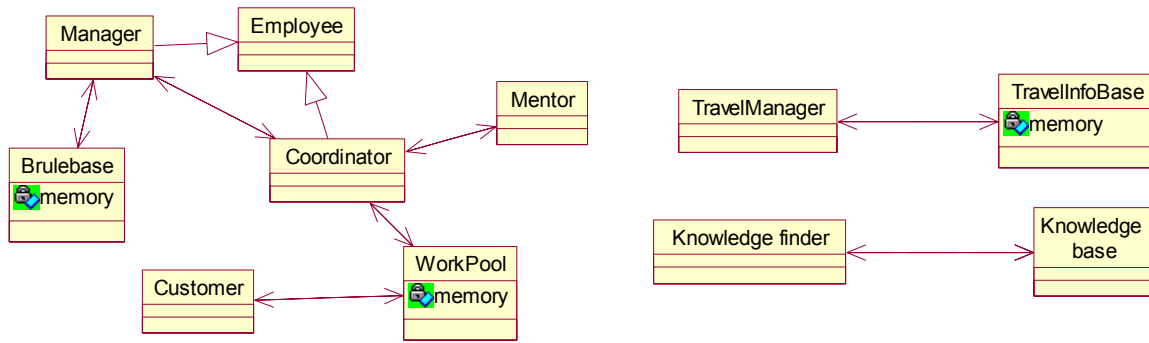


Figure 2: Role models for the telephone repair service teams case study

4.1 Role Identification

In order to model the above system in terms of roles, the first thing to do is to identify the roles involved in the case study. According to [7] a way to identify roles in an application domain is to start from identifying use cases, associating each use case with a goal, creating a goal hierarchy from the use case hierarchy and coalescing semantically relevant goals in roles. For the purpose of our example we consider the following three use cases: *Teamwork coordination*, *Travel management* and *Work Knowledge Management*.

Applying the methodology suggested in [7], the following roles can be identified (fig. 2):

1. *Employee*: This role describes generic behaviour of the members of the customer service teams. An example of this type of behaviour is accessing common team resources including work practice announcements and business news.
2. *Coordinator*: The *Coordinator* role describes the behaviour required to coordinate the work of a field engineer. This includes bidding for and obtaining repair work tasks from a work pool, negotiating with other workers and the team manager as required and scheduling and rescheduling work task execution.
3. *Manager*: The *Manager* role models the behaviour of the team manager. This includes confirming task allocation, monitoring work and ensuring that business rules are followed.
4. *Mentor*: The *Mentor* role provides assistance to field engineers for non-technical issues.
5. *WorkPool*: The *WorkPool* role maintains a pool of telephone repair requests. Customers interact with this role to place requests and engineers interact with this role to select tasks to undertake.
6. *Customer*: The *Customer* role models the behaviour of a customer. It involves placing telephone repair requests,

receiving relevant information and arranging appointments with field engineers.

7. *Brulebase*: This role maintains a database of business rules. It interacts with manager providing information about the current work policy of the business.
8. *TravelManager*: The *TravelManager* role provides travel information to the field engineer including current location, traffic information and optimal route to next telephone repair task.
9. *TravellInfoBase*: This role store travel information from various travel resources i.e. GPS and traffic databases.
10. *Knowledgefinder*: This role searches for experts and obtains assistance regarding complex work tasks.
11. *Knowledgebase*: The *Knowledgebase* role maintains and manages a database of expertise about telephone repair tasks.

4.2 Specifying Design Constraints

In fig. 3, compositional constraints for the roles described in section 4.1 are specified in *RCL (Role Constraint Language)*.

RCL is simple declarative constraint language we introduced to represent design constraints on agent and role characteristics. Any non-obvious use of *RCL* in fig. 5 is described below together with the relevant design constraints. *RCL* itself is described in detail in [5].

Roles in *RCL* are specified in a manner similar to programming languages. Roles that directly manipulate databases require access to some storage space. This is modelled by the performance variable *memory*. The memory requirements of each role are different. For example, *Travellinfobase* and *Knowledgebase* require twice as much memory as *Workpool* and *Brulebase*.

Part of the definition of the characteristics of the *Manager* role is shown in more detail in fig. 3. The collaborators of the *Manager* role are the *Coordinator* and *Brulebase* roles

```

/* ROLE DEFINITIONS */
Role employee, coordinator, mentor,
  customer, travelmanager,
  knowledgefinder;

Role workpool, brulebase, workerassistant;
  travelinfobase, knowledgebase {
  int memory;
}
  workpool.memory = 1;
  brulebase.memory = 1;
  travelinfobase.memory = 2;
  knowledgebase.memory = 2;
  workerassistant.memory = 1;

Role manager {
  collaborators = {Coordinator,
                  Brulebase};
  protocols = {contracting};
}

/* ROLE CONSTRAINTS */
in(employee, coordinator);
in(employee, manager);

not(customer, employee);
not(customer, travelinfobase);
not(customer, knowledgebase);
not(mentor, manager);
not(manager, coordinator);

and(mentor, employee);

merge(coordinator, travelmanager,
      knowledgefinder,
      workerassistant);

/* GENERAL CONSTRAINTS */
Constraint Y {
  forall a:Agent {
    a.memory <= 2
  }
}

```

Figure 3: Compositional constraints for telephone repair service teams roles

and its interaction protocol is the Contract Net. The Employee role is contained in both *Manager* and *Coordinator* roles. Furthermore, a *Manager* cannot coexist with *Mentor* or *Coordinator* and for security purposes a *Customer* cannot coexist with *Employee*, *Travelinfobase* or *Knowledgebase*. In order for an agent to be *Mentor* it must also be an *Employee*.

When an agent plays all three *Coordinator*, *TravelManager* and *KnowledgeFinder* roles then overheads occur in synchronising results from these three different activities. This is modelled as a merging of the *Coordinator*, *Travelmanager* and *Knowledgefinder* resulting to the *WorkerAssistant* role. The *WorkerAssistant* role requires some storage space to store intermediate synchronisation results.

An example of non-functional requirements is the limit to the memory each agent could occupy. In this case study, agents supporting field engineers should be able to operate in PDAs with limited amount of memory. This is modelled as a general design constraint on the performance variable *memory*. A possible agent organisation satisfying the above design constraints is depicted in fig. 4.

5. CONCLUSIONS - FURTHER WORK

Existing approaches to agent organisation design do not pay enough attention to semi-automating the transformation of analysis into design. In this paper, a simple role algebra enabling automatic allocation of roles to agents has been introduced. This approach enables reuse of organisational design settings by representing them as role models being able to be manipulated considering the proposed role algebra.

However, there are issues that have not been addressed yet. For example, agents can play different roles in different contexts and hence the possible contexts should be considered when designing agent organisations. Furthermore, it is planned to use the role algebra to enable allocating and de-allocating roles to agents dynamically on run-time.

6. ACKNOWLEDGMENTS

This work has been supported by BT under a grant from the office of the Chief Technologist (No. ML816801/MH354166).

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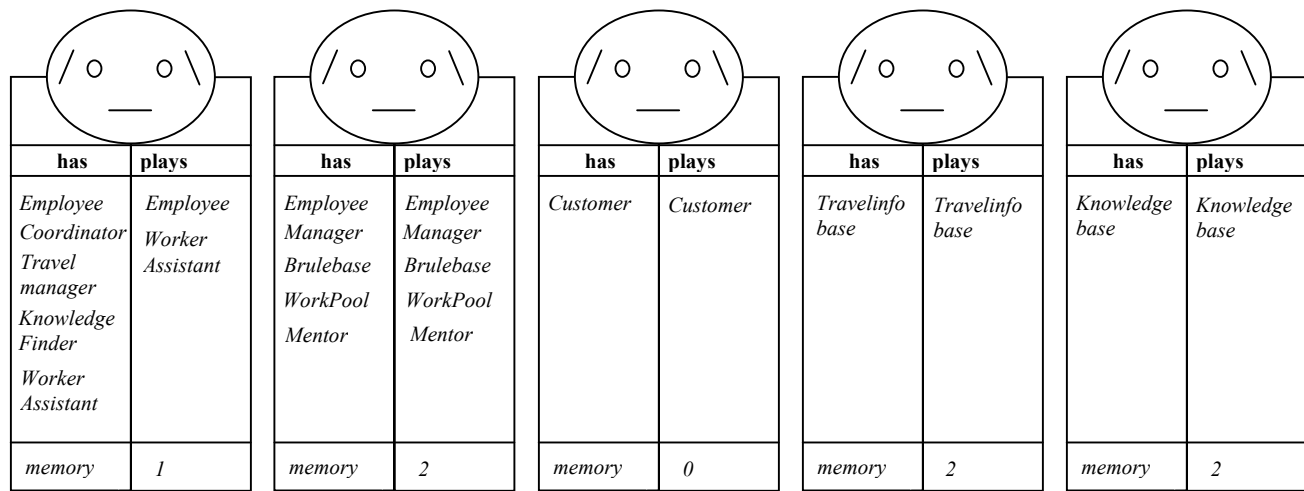


Figure 4: Agent types for the telephone repair service teams case study

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