

Response Fusion in Multi-Agent Environment

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Abstract: Multi agent environment are often complex, while each member of agent community has vision about only a part of the environment. In such environment, information fusion of agent community is vital to attain a better accuracy or quality of information. Agents have different ability and can access to information sources with different degree of credibility. As a result, information which is obtained by agents, should be fused with considering their response credibility. In this research, at first we have introduced a method to obtain agent credibility based upon the opinion of agent community. In the proposed method, we measure the possibility of credibility for each agent. Next, we assume that in response to a query, every agent produces a fuzzy answer set in response to a query. On this assumption, a new fuzzy operator with some desired properties for agent responses fusing with their credibility consideration is proposed.

Key words: Multi-agent, information fusion, fuzzy operators, possibility theory

INTRODUCTION

One of the main purpose in agents communication is to achieve the goals better^[10]. Suppose that in response to a query, each agent can produce a response set which has a level of uncertainty. Uncertainty in agent response may be attributed to two main reasons, namely, deficiency in agent capability and the ambiguity of application information. The first aspect is generally due to agent design/implementation deficiency. The second aspect is due to information overload. For example, in an environment such as the Internet, properties like inaccessibility, non-deterministic and dynamic nature of the information space are sources of agent imprecise decisions. Our goal is the utilization of the other agents in order to reduce the uncertainty and consequently to obtain response with higher quality. For this purpose, the query should propagate in multi-agent environment and agents' response to be aggregate.

For aggregation, these issues should be considered. Agent responses have different degree of accuracy, so final response should be a function of each agent response with considering the degree of credibility. In other words, the opinion of agent with higher credibility has more effect on final answer and vice versa.

For each agent response, the degree of its credibility should be determined. In order to fuse agent responses, we need an operator with considering the problem of credibility degree of resources.

Credibility assignment can be user generated or sanctioned knowledge base^[2]. In sanction based system a central agent decides about the credibility of the other agents. As there is no centralized element in multi-agent environment, sanctioned knowledge base methods might not be used. In our suggested method, the opinion of agents' community is used to assign the credibility to each agent. There are currently some works based on weighting and probability theory for credibility assignment^[4,12,13,14,15]. Also bayesian^[5,6] and fuzzy approach^[7,8] are used for credibility assessment. Also in our work the possibility of credibility is assigned to each agent, not the probability of credibility. As the credibility, value assigned by each agent to the other agents is an approximate value and with some uncertainty, assigning credibility possibility is more appropriate than credibility probability.

In the next step, we assume that when an agent receives a query, it propagates the query to the other agents to attain their abilities and opinions. After receiving a query, each agent generates a fuzzy answer set. We need a fusion operator, which considers agent credibility to fuse these answers sets with considering agent credibility. For information fusion by considering source credibility, an operator is suggested by Yager^[13] and Prade^[9]. A problem with this operator applying to fuse agent answers is that the operator on the final decisions does not reflect the low credibility of all agents within the multi-agent environment. Therefore, an environment with low creditable decision makers

cannot be distinguished from the ones with highly creditable agents. Consequently, a comparison of agent community response is not possible. To resolve this problem, with considering the credibility of the agents, an improved version of this decision fusion operator based upon the assumption that each agent generates a fuzzy decision set is presented.

MATERIALS AND METHODS

Multi-agent environment is an infrastructure that enables collaborative decision-making. Decision makers may have different degrees of credibility. I $A = \{A_1, A_2, A_3, \dots, A_N\}$. Each of these agents collects information from its accessible knowledge resources and has special capability of decision-making. In this regard, each agent, such as A_i , defines an assigned credibility possibility distribution for each subject.

$$AsscrePoss_i = \cup crePoss_{s;ij}$$

where, $crePoss_{s;ij}$ is the degree of credibility possibility assigned by the i th agent to the j th one, while:

$$0 \leq crePoss_{i1} \cup crePoss_{i2} \cup \dots \cup crePoss_{in} \leq 1$$

$$\forall DM_i \in DM$$

DP_N is the N th decision problem, D_k is the decision which is made for DP_N and R_N is the membership degree of D_k To decision set which is made against DP_N .

The $crePoss_{s;ij}$ values for each subject are kept in a matrix called the credibility matrix for each subject, as shown in Fig. 1.

CREDIBILITY ASSIGNMENT TO AGENTS

After the matrix $CrePoss$ is established, the credibility possibility of each agent $crePosij$, should be influenced by the opinions of the other agents.

Credibility assignment to each agent is defined by a fuzzy relation implemented as a max-min composition. At each instance of time, $t+1$, the max-min composition influences the opinion of each agent, $crePoss_{ij}^{t+1}$ by the others opinions as follows: Suppose there is a group of N agents in multi-agent environment, indexed by the set

$$crePoss_{ij}^{t+1} = \max \left\{ crePoss_{ik} \wedge crePoss_{kj}^t \right\} \quad k = 1, \dots, N$$

$$, crePoss_{ij}^1 = crePoss_{ij}$$
(1)

$$\begin{bmatrix} crePoss_{s11}(Subject_m) & crePoss_{s12}(Subject_m) & \dots & crePoss_{s1n}(Subject_m) \\ crePoss_{s21}(Subject_m) & crePoss_{s22}(Subject_m) & \dots & crePoss_{s2n}(Subject_m) \\ \dots & \dots & \dots & \dots \\ crePoss_{sN1}(Subject_m) & \dots & \dots & crePoss_{sNm}(Subject_m) \end{bmatrix}$$

Fig. 1: Credibility possibility matrix

Our goal is to gain a possibility distribution for the credibility of the agents by a distributed model. In our model, $crePoss_{s;ij}$, the credibility of the agent A_i is dependent on, the amount of the credibility that all agents DM_k for $k = 1$ to N , have assigned to the i th agent. The credibility of an agent, $crePoss_{s;ij}$, is a function of $crePoss_{s;ij} \quad k = 1, \dots, N$.

$$crePoss_i = \bar{F}(crePoss_{ki}, crePoss_k), k = 1..N \quad (2)$$

Here, \bar{F} indicates the max-min function. To apply the max-min function, a set of equations $\overline{crePoss} = \overline{crePoss} \circ P^n$ is established where, vector $\overline{crePoss} = \langle crePoss_1, crePoss_2, \dots, crePoss_N \rangle$ indicates the credibility possibility distribution for the agents community; \circ is the max-min operator and P is a matrix whose components are the degree of credibility of each agent from the point of view of the other agents.

Theorem 1: If an agent A_i increases $crePoss_{ik}$, then from the point of view of A_i the A_k 's capability in determining the credibility of the other agents will not be reduced.

Proof: Let the credibility value of the k th agent from the point of view of the i th agent, $crePoss_{s;ik}$, changes from α to β such that $\beta > \alpha$. In this case, $\alpha \wedge crePoss_{kj}^t \leq \beta \wedge crePoss_{kj}^t$, where j represents any agent in the multi-agent environment. As a result $crePoss_{s;ik} \wedge crePoss_{kj}^t$ will not decrease and the possibility that $\beta \wedge crePoss_{kj}^t$ be the maximum value of $\{ crePoss_{ip} \wedge crePoss_{pj}^t \} \quad P = 1, \dots, N$ will increase. Since $crePoss_{kj}^t$ indicates the credibility degree of A_j in judgment of A_k at time t , the role of A_k in determination of the credibility of A_j will not decrease.

Theorem 2: If $crePoss \circ AssCreM = crePoss$ Then: $crePoss \circ AssCreM^n = crePoss^{[2]}$.

Considering theorem 2, to work out the value of the credibility vector, $crePoss$, instead of using the relation $crePoss \circ P^n = crePoss$, the relation

crePoss₀ AssCreM = crePoss can be used to obtain a distribution, crePoss. Such a distribution is called stationary distribution.

Example 1: Suppose there are three agents $A = \{A_1, A_2, A_3\}$, a max function, f and a min function, g . It is desirable to calculate the credibility possibility of the second agent such that the condition of the function F , defined in relation (2), is satisfied.

Using theorem 2 and Eq. 2, the possibility measure of the second agent credibility computes as follows:

$$\begin{aligned} \text{crePoss}_2 &= f(g(\text{crePoss}_1, \text{crePoss}_{12}), \\ &g(\text{crePoss}_2, \text{poss}_{22}), g(\text{crePoss}_3, \text{poss}_{32})) \end{aligned}$$

where, $\text{crePoss}_1, \text{crePoss}_2$ and crePoss_3 represent the credibility of the first, second and third agents respectively and crePoss is the credibility matrix.

DECISION FUSION

As described above, for a collection of N agents, indexed by the set $A = \{A_1, A_2, \dots, A_N\}$, the credibility possibility could be estimated for each of the agents, based upon the other agents opinions. The distribution of the estimated credibility possibility values is represented as a vector $\text{crePoss} = \langle \text{crePoss}_1, \text{crePoss}_2, \dots, \text{crePoss}_N \rangle$, where crePoss_i is the credibility of A_i . In this research, the vector $\overline{\text{crePoss}}$ is applied to fuse decisions made by the members of agent community. In response to any decision making problem such as q , A_i generates a fuzzy decision set $\overline{R}_i(DP) = \{D_1, D_2, \dots, D_m\}$, with the perception of its accessible knowledge environment and its belief, such that each fuzzy member $D_k \in \overline{R}_i(DP)$ is one of the m decisions made by DM_i . The number of selected decisions, m , may vary for different agents. The membership degree of D_k to the final set of decisions or responses $\overline{R}_F(DP)$ is represented as $\overline{R}_F(DP, D_k)$ such that $0 \leq \overline{R}_F(DP, D_k) \leq 1$. The goal is to estimate $\overline{R}_F(DP, D_k)$ based upon the possibility distribution of agents' credibility, crePoss , and the membership degree of D_k to the decision set, D , of each agent. Estimating the membership degree, $\overline{R}_i(q, D_k)$, is formalized as follows:

$$\begin{aligned} \overline{R}_F(DP, D_k) &= f(\text{crePoss}_i, R_i(DP, D_k)) \\ 0 \leq \overline{R}_F(DP, D_k) &\leq 1 \quad \forall A_i \in A \end{aligned} \quad (3)$$

We choose function F such that it has the following eight properties which are required for any information fusion operator^[14].

Property 1: Monotonicity with respect to the membership degree of each decision to decision set:

$$\text{Let} \quad R_F(DP, D_k) = f(\text{crePoss}_i, R_i(DP, D_k)), \quad \forall A_i \in A, \quad i = 1, \dots, N$$

$$R_F(DP, D_1) = f(\text{crePoss}_i, R_i(DP, D_1)) \quad \forall A_i \in A \quad \text{and} \\ R_i(DP, D_k) \geq R_i(DP, D_1) \quad \forall A_i \in A$$

$$\text{Then} \\ R_F(DP, D_k) \geq R_F(DP, D_1).$$

It implies that if all the members of agent community, DM , make two decisions D_k and D_l then based on the assumption that all agents agreement on D_k being either identical to or more acceptable than D_l , it can be concluded that D_k has greater membership degree to final decision set than D_l has.

Property 2: Monotonicity with respect to credibility possibility:

$$\text{If} \quad R'_F(DP, D_1) = f(\text{crePoss}'_i, R'_i(DP, D_1)), \quad \forall DM'_i \in DM'$$

$$R_F(DP, D_k) = f(\text{crePoss}_i, R_i(DP, D_k)) \quad \forall DM_i \in DM \quad \text{and} \\ R_i(DP, D_k) = R'_i(DP, D_1), \text{crePoss}_i \geq \text{crePoss}'_i \quad \text{then} \\ R'_F(DP, D_1) \geq R_F(DP, D_k).$$

Assume D_l and D_k are two decisions made by DM_i and DM'_i in response to a DP respectively while $R'_i(DP, D_1)$ and $\text{crePoss}'_i \geq \text{crePoss}_i$ $\forall DM_i \in DM, DM'_i \in DM'$. In this regard, the membership degree D_l to final decision set, $R'_F(DP, D_1)$, will be more than or equal to the membership degree of D_k to final Decision set, $R_F(DP, D_k)$. This property is applicable when two or more knowledge multi-agent are compared.

Property 3: Pointwiseness property: The determination of $R_F(DP, D_k)$ value depends only on $R_i(DP, D_k)$ and $\text{crePoss}_i \quad \forall DM_i \in DM$ and is independent of $R_i(DP, D_l) \quad \forall DM_i \in DM, l \neq k$.

Property 4: If the possibility of credibility of j th agent is more than the possibility of credibility of the k th agent, $\text{crePoss}_j > \text{crePoss}_k$, then the ability of j th agent in

determination of final decision set should be equal to or more than the ability of kth agent in determination of final decision set. In other words, the less credible agent should have fewer roles in determination of final decision set and vice versa.

Property 5: If credibility possibility of an agent is zero, then its opinion has no effect on the result of function f.

Property 6: If the credibility possibility of an agent is one, then its decision impact should not be reduced and its constraints on the answer should be imposed completely.

Property 7: Commutatively property: Indexing of agents should not affect the final decision set. For instance, if our multi-agent environment has two agents indexed one and two then:

$$f((crePoss_1, R_1(DP, D_k)), (crePoss_2, R_2(DP, D_k))) \\ = f((crePoss_2, R_2(DP, D_k)), (crePoss_1, R_1(DP, D_k)))$$

Property 8: $R_F(DP, D_1) < \max(crePoss(DM_i)) \quad \forall D_1 \in D$

A community of agents in multi-agent environment can not produce a decision which its membership degree to the final decision set is greater than the credibility degree of most credible agent.

For example if the $\max(crePoss_i) = 0.8$ then $\max(R_F(DP, D_1)) \leq 0.8 \quad \forall A_i \in A, \forall D_1 \in D$

SOLUTION OF THE EQUATION SET

In order to solve the equation set $crePoss \circ crePossM = crePoss$, the fuzzy markov chain model^[1] is used. Since $crePossM$ is a fuzzy transitive matrix, $crePoss$ should be an eigen fuzzy set. Also, since $crePoss$ is a possibility distribution, it is appropriate to obtain the greatest eigen fuzzy set satisfying the equation set $crePoss \circ crePossM = crePoss$.

Example 2: Suppose that the credibility matrix $crePossM$ is as shown Fig. 2. It is desired to obtain the credibility vector, $crePoss$.

$$crePossM = \begin{bmatrix} 0.1 & 0.7 & 0.2 & 0.8 & 0.7 \\ 0 & 0.6 & 0.4 & 0.3 & 0.5 \\ 0.3 & 1 & 0 & 0.1 & 0.4 \\ 0.3 & 0.3 & 0.8 & 0.1 & 0 \\ 0 & 0 & 0.7 & 0.5 & 0 \end{bmatrix}$$

Fig. 2: CrePoss matrix for example 2

For obtaining the greatest eigen fuzzy set we use the algorithm which presented in^[15].

If we have $x_0 \circ P = P$ equation the stages of algorithm are as follows:

- Determine first x_1 with the elements corresponding to the greatest element of column of P
- Compute $P_2 = P \circ P$ and determine the greatest elements in each column of P_2 they give x_2
- Compare x_2 with x_1 : if they are different, compute $P_3 = P \circ P_2$ to get x_3
- Compare x_3 with x_1 : if they are different, compute $P_4 = P \circ P_3$ to get x_4 , stop

It is found m such that $x_{m+1} = x_m$, that is $x_m = x_m \circ P$.

Applying this algorithm, the greatest eigen fuzzy set, or in the other words the possibility distribution vector, $crePoss$ and the possibility of $crePoss$ will be as follows:

$$CrePoss_x = [0.3 \quad 0.6 \quad 0.5 \quad 0.5 \quad 0.5]$$

possibility($crePoss_x$) = $\max(0.3, 0.6, 0.5, 0.5, 0.5) = 0.6$

So far the possibilities of credibility for each of agents according to the other agents' opinions is evaluated. In the next step, the evaluated credibility values are used to fuse the fuzzy decision set of the members of agents' community.

SUGGESTED OPERATOR FOR DECISION FUSION

In this research, to evaluate RF function, an information fusion operator considering the properties discussed in decision fusion section is presented. Some works on information fusion operator based on source credibility have been done by Dubios and Prade^[3].

According to relation 2, This operator modifies rank of answers and then selects the minimum of these modified values. The drawback of this operator is that it has not monotonic properties with respect to credibility possibility. Therefore, it could not be used for comparing different multi-agent environment or aggregating of decision sets of more than one multi-agent environment. In order to use the suggested operator, considering the degree of credibility possibility of each agent, $\overline{R}_i(DP, D_k)$ is modified to $\overline{R}'_i(DP, D_k)$.

$$\overline{R}'_i(DP, D_k) = R_i(DP, D_k) \vee (1 - crePoss_i) \quad (4)$$

Then we use of $\overline{R}'_i(DP, D_k)$ to gain $R_F(DP, D_k)$ in the following way:

Table 1: Response of agents to each query

D5	D4	D3	D2	D1	
N/A	N/A	0.4	0.6	0.8	R1
0.8	N/A	N/A	1	0.6	R2
1	0.3	0.9	0.7	0.4	R3
N/A	0.8	0.6	0.8	0.5	R4
N/A	0.1	0.3	0.7	N/A	R5

$$RG(D1) = T(0.8, 0.6, 0.5, 0.5, 0.5) = \min(0.8, 0.6, 0.5, 0.5, 0.5) \\ \wedge \max(0.3, 0.6, 0.5, 0.5, 0.5) = 0.5$$

Table 2: Modified Response considering credibility

D5	D4	D3	D2	D1	
0.7	0.7	0.7	0.7	0.8	R ₁ '
0.8	0.4	0.4	1	0.6	R ₂ '
1	0.5	0.9	0.7	0.5	R ₃ '
0.5	0.8	0.6	0.8	0.5	R ₄ '
0.5	0.5	0.5	0.7	0.5	R ₅ '

$$R_F(DP, D_k) = \min(R'_i(DP, D_k)) \wedge \max(\text{crePoss}_i) \quad (5) \\ i = 1, 2, \dots, N$$

Example 3: Considering the possibility distribution of example 2, crePoss_x , as credibility values and Table 1 as decision sets for agents' community then the modified memberships are the values presented in Table 2. The membership degree of D1 is obtained in the following way.

PROOF THE CORRECTNESS OF THE OPERATOR

In this research, it is proved that the new decision fusion operator, R_f , introduced in previous section, satisfies properties number 1 to 8 discussed in decision fusion section.

Property 1: If all agents DM_i believe that the rank, R_i , of decision D_k for the problem DP is greater than rank D_l then considering the credibility possibility of the agents, the modified rank, R'_i , of decision D_k is greater than $R'_i(DP, l)$. In the other words;

$$\text{If } R_i(DP, D_k) \geq R_i(DP, D_l) \forall DM_i \in DM$$

then considering T-conorm (here \vee) - $R'_i(DP, D_k) \geq R'_i(DP, D_l)$.

Therefore;

If $R'_p(DP, D_k)$ is the smallest element in the set $R'_i(DP, D_k) \forall DM_i \in DM$ then there is an element less than or equal to $R'_p(DP, D_k)$ in the set $R'_i(DP, D_l) \forall DM_i \in DM$. In the other words:

$$\min(R'_i(DP, D_k)) \geq \min(R'_i(DP, D_l)) \forall DM_i \in DM$$

Considering the property of T-norm operators, we have:

$$\min(R'_i(DP, D_k)) \wedge \max(\text{crePoss}_i) \geq \\ \min(R'_i(DP, D_l)) \wedge \max(\text{crePoss}_i) \forall DM_i \in DM'$$

Consequently $R_F(DP, D_k) \geq R_F(DP, D_l)$.

Therefore, the introduced operator satisfies property one.

Property 2: If there are two collection of agents D and D^* such that:

$$(\text{crePoss}_{i,*}) \geq (\text{crePoss}_i) \forall D_i \in D, \forall D_{i,*} \in D^*$$

Then $\max(\text{crePoss}_{i,*}) \geq \max(\text{crePoss}_i)$.

In addition, it is obvious that:

$$R_F(DP, D_k) \leq \max(\text{crePoss}_i)$$

and

$$R_F^*(DP, D_l) \leq \max(\text{crePoss}_{i,*})$$

As a result $R_F(DP, D_k) \leq R_F^*(DP, D_l)$.

Therefore, it is observed that the introduced operator, RF , satisfies property two.

Property 3: RF satisfies pointwiseness property as $R_i(DP, D_k) \forall D_i \in D$ and crePoss_i are only used to calculate $R_F(DP, D_k)$.

Property 4: The higher the credibility possibility of agent, the higher its effect on the final response or decision RF . According to relation (3), $R_F(DP, D_l)$ is a conjunction of two parameters. The first parameter is $\max(\text{crePoss}_i) \forall DM_i \in DM$ and the second is $\min R'_i(DP, D_l) \forall DM_i \in DM$. Considering the first parameter, it is observed that only the highest credible agent DM_i determines the value of the first parameter.

Considering the second parameter which is a conjunction of $(1-\text{crePoss}_i)$ and $R_i(DP, D_l)$, it is observed that if:

$$\text{crePoss}_j \geq \text{crePoss}_k$$

and

$$1 - \text{crePoss}_j \leq 1 - \text{crePoss}_k$$

then according to the T-conorm property the following relations are always true:

$$\begin{aligned} R'_j &> 1 - \text{crePoss}_j \\ R'_k &> 1 - \text{crePoss}_k \end{aligned}$$

it can be concluded that $R'_j \geq R'_k$. As a result R'_j could not be the min (R'_i) $\forall DM_i \in DM$, so it has no effect in determination of RF.

So the introduced operator satisfies the forth property.

Property 5: If the credibility possibility of the ith agent is zero, then according to the relation (2), the ith agent has no effect on the value of RF, because:

$$\begin{aligned} \text{crePoss}_j = 0 &\Rightarrow 1 - \text{crePoss}_j = 1 \Rightarrow \\ R'_j(DP, D_k) &= 1 \quad \forall D_k \in D \end{aligned}$$

Moreover, since:

$$\begin{aligned} R_F(DP, D_k) &= \min(R'_1(DP, D_k), R'_j(DP, D_k)) \\ &\wedge \max(\text{crePoss}_1, \text{crePoss}_j) \\ &\quad \forall DM_i \in DM - \{DM_j\} \\ R_F(DP, D_k) &= \min(R'_1(DP, D_k), 1) \wedge \max(\text{crePoss}_1, 0) \\ &\quad \forall DM_i \in DM - \{DM_j\} \\ R_F(DP, D_k) &= \min(R'_1(DP, D_k) \wedge \max(\text{crePoss}_1)) \\ &\quad \forall DM_i \in DM - \{DM_j\} \end{aligned}$$

Property 6: If the credibility possibility of the ith agent is one, then according to the relation (2), the ith decision-maker opinion will be imposed completely as it is. In the other words:

$$\begin{aligned} \text{crePoss}_j = 1 &\Rightarrow 1 - \text{crePoss}_j = 0 \Rightarrow \\ R'_j(DP, D_k) &= R_j(DP, D_k) \quad \forall D_k \in D \end{aligned}$$

Now, substituting the values of crePoss and $R'_j(DP, D_k)$ in relation (3), the following relation will be resulted:

$$\begin{aligned} R_F(DP, D_k) &= \min(R'_1(DP, D_k), R_j(DP, D_k)) \wedge 1) \\ &\quad \forall DM_i \in DM - \{DM_j\} \\ R_F(DP, D_k) &= \min(R'_1(DP, D_k), R_j(DP, D_k)) \\ &\quad \forall DM_i \in DM - \{DM_j\} \end{aligned}$$

The above relation shows that only the jth agent decision, $R_j(DP, DK)$, directly affects the final decision. The impact of the other agents decisions depends on their credibility possibility values.

Property 7: Since the Max and Min operators have commutatively property then considering relation (3) it is deduced that our fusion operator also satisfies the property number 7.

Property 8: According to relation (3), RF, is computed as a conjunction of $\min(R'_i(DP, D_k))$ and $\max(\text{crePoss}_i)$ then rank of the final decision, RF, cannot exceed the maximum value of the credibility possibility of the agents.

RESULTS AND DISCUSSION

Our goal is to fuse agent responses to a query in order to improve the accuracy of answer and reduce the uncertainty. As agents have different degree of credibility in response to a query, agent responses should be fused with considering the answers credibility. In this research, we first suggest a method for assigning credibility to each agent response. This approach is based on possibility theory. According to this approach, we reach a fuzzy equation set which is solved by use of fuzzy markov chain. The assigned credibility value is of the type of possibility and have a fuzzy nature. In the next stage, we assume that in response to any query each agent produce a fuzzy answer set. Afterwards we suggest a new operator for fusing these fuzzy answer sets with considering response credibility. This operator has a set of properties which is necessary for information fusion. We discussed eight properties in this regard and then we proof that this operator has these properties. The proposed operator modifies the rank of agents' answers considering the credibility of agent which gives it and then obtains a final answer with higher degree of credibility.

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