Crowdsourcing of Computational Problem Solving

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Abstract

Computational problems can be specified by logical statements interpreted in a computable model (a.k.a. claims). Semantic Games (SGs) of claims, a well-researched area, provide novel answers to crowdsourcing challenges yet with several limitations. Most notably that SGs provide a binary interaction mechanism that requires both participants to hold contradictory positions on the underlying claim. We provide a comprehensive analysis of the limitations of SGs when used for crowdsourcing and propose a new concept, called the Contradiction-Agreement Game (CAG), which builds on SGs and has desirable properties for successful crowdsourcing. We describe a proof of concept implementation of a CAG-based crowdsourcing platform for computational problems. Our system uses a modular construct, called a lab, to group related claims and to solve labs incrementally through lab relations which are themselves captured as labs.

Our proposed system has important applications in addition to crowdsourcing computational problem solving: (1) The collaborative and self-evaluating nature of SGs provides a peer-based evaluation system for MOOCs on formal science topics. The peer-based evaluation is guaranteed to be fair and saves significant time for the teaching staff. (2) it provides a lower barrier of entry to making contributions to formal sciences through game play. It is a significant help to scientists to test claims using the crowd.

1 Background

1.1 Crowdsourcing

Crowdsourcing has become an important problem solving approach that enables us to tackle large scale problems that require human intelligence to solve. Crowdsourcing has been successfully applied to several problems over the past decade. Including, labeling images indexed by Google on the web [28], discovering protein foldings [12], synthesizing proteins [8] and building the Wikipedia.

It is our goal to apply crowdsourcing to solve computational problems. To achieve this goal, there are four challenging questions that we need to address [13]:

1. What contributions can users make?
2. How to evaluate users and their contributions?
3. How to combine user contributions to solve the target problem?
4. How to recruit and retain users?

1.2 Logical Games and Computational Problems

Logical games have a long history going back to Socrates. More recently, they became a familiar tool in many branches of logic. Important examples are Semantic Games (SGs) used to define truth, back-and-forth games used to compare structures, and dialogue games to express (and perhaps explain) formal proofs [23], [14], [18].

SGs are played between two players, the *verifier* and the *falsifier* [1]. An instructive way of viewing SGs is in their extensive form, which essentially is a tree structure with the root labeled by the formula ϕ , the subsequent labeled nodes representing the subformulas of ϕ, and the vertices labeled by the actions of the players.

In the theory of SGs, logical statements interpreted in a computable model (a.k.a. claims) derive their meaning from the games played by the rules prompted by the logical connectives encountered in the claims [24]. The existence of a winning strategy for the *verifier* implies that the underlying logical statement is indeed *true* and the existence of a winning strategy for the *falsifier* implies that the underlying logical statement is indeed *false*.

Players need to solve *computational problems* in the course of playing SGs. For example, the falsifier of the $prime(7) = \forall k \; s.t. \; 1 < k < 7 : \neg divides(k, 7)$ needs to compute the factors of 7. Similarly, claims can be used to logically specify computational problems. For example, consider the problem of finding the factors of a given natural number $factors(n)$. This problem can be logically specified using the claim $\forall n \exists s : \forall k : divides(k, n) \Leftrightarrow k \in s$. In SGs derived from this claim, the verifier needs to correctly solve $factors(n)$ in order to win.

A computational problem can be logically specified as a claim about the relation between either (1) the input properties and the output properties, or (2) the input properties and the output finding process properties such as resource consumption.

[1] Other names has been also used in the literature such as I and *Nature*, *Proponent* and *Opponent*, and *Alice* (female) and *Bob* (male).

2 Thesis

Our thesis is that semantic games of interpreted logic statements provide a useful foundation for building *successful* crowdsourcing systems for solving computational problems.

2.1 Rationale and Limitations of Semantic Games

SGs of claims provide attractive answers to the four challenging questions of crowdsourcing systems. However, these answers are only valid in a limited context. A *successful* SG-based system must generalize SGs to a much wider context and improve on the way SGs address these four challenging questions, whenever possible.

An example of such limitation is that SGs define an interaction mechanism between two users only. A successful SG-based crowdsourcing system must provide a Crowd Interaction Mechanism (CIM) on top of SGs that decides which SGs to be played. To decide on a game to be played, the CIM must decide on a claim, a user to take on the verifier position and a user to take on the falsifier position. On one hand it is important that the CIM relies on user preferences to enhance the user experience, ensure that user contributions are potentially correct, and to ensure the fairness of SG-based evaluation. On the other hand, the overall system would be ineffective if the CIM was just a proxy to users' preferences because the CIM would no longer be able to *drive* the user interaction. For example, it would be impossible to hold an SG between two arbitrary users unless they hold contradictory positions on the same claim.

2.1.1 User Contributions

During the course of playing an SG, users make two kinds of *formal* contributions: positions and supporting actions. These two kinds of contributions can be extracted from SG traces as follows:

The trace of an SG can be represented as a *directed line graph* where nodes represent the state of the SG and edges represent transitions. The state is a tuple consisting of a claim and a pair of players, the player taking the verifier position and the player taking the falsifier position. For example, the tuple $\langle c, p_1, p_2\rangle$ represents a state where p_1 is the player taking the verifier position and p_2 is the player taking the falsifier position on claim c. A labeled transition represents a supporting action while an unlabeled transition represents an implied action. Implied actions are automatically carried out by the system. An example of implied actions is given by: $\langle \neg c, p_1, p_2\rangle \rightarrow \langle c, p_2, p_1\rangle$. Supporting actions are either attacks or defenses and they involve an additional parameter that one of the users must provide. For example, the transition $\langle \forall x : p(x), p_1, p_2\rangle \xrightarrow{x_0} \langle p(x_0), p_1, p_2\rangle$ is an attack made by p_2, where x_0 is a counter example provided by p_2.

Apart from playing SGs, users can still contribute by improving their own SG playing strategies. By doing so, players are able to spot more problems in

the positions taken by their opponents in future games. Because users have to follow a well defined formal protocol B to play an SG, this enables users to *automate* the execution of their strategies into *avatars*. Algorithms used in avatars are themselves yet another potential formal contribution (see Section 2.2).

2.1.2 Evaluating Users

SGs provide an *objective* and *self-sufficient* approach to assess the *relative strength* of users. Simply put, the winner of an SG is considered *stronger* than the loser. This approach is fundamentally different than the current evaluation schemes used in crowdsourcing systems such as: gold standards, trusted workers and probabilistic oracles, and disagreement-based schemes [16].

Disagreement-based schemes evaluate the *absolute strength* of users based on how often the user's contribution is "correct" where a "Correct" contribution is defined to be *similar* to the "majority vote". SG-based evaluation is independent of the "correctness" of user contributions. Instead SG-based evaluation can *objectively* judge one contribution to be "better" than the other. It is worth noting that the "better" contribution is not always necessarily *similar* to the "majority vote".

SG-based evaluation is said to be *self-sufficient* because, unlike gold standard evaluation, it is not based on a set of pre-populated test cases. Instead, the two users test each other.

It is important to evaluate users' strength based on their performance in a large number of SGs. The naïve approach of summing the number of SGs the user won is unlikely to be fair due to several concerns that give one group of players an advantage over another group of players. A comprehensive list of these concerns is given by:

1. Users can be at an advantage (or at a disadvantage) if they participate in more SGs where they are at an advantage (or at a disadvantage). A player is at an advantage (or at a disadvantage) in an SG if either the claim **(CONCERN 1.a)** or the position **(CONCERN 1.b)** is only forced on their adversary (or only forced on them).

2. Users can be at an advantage (or at a disadvantage) if they participate in more (or fewer) than the average number of SGs played by their counterparts **(CONCERN 2)**.

3. Users can be at an advantage (or at a disadvantage) if they participate in more SGs against other weaker (or stronger) users **(CONCERN 3)**.

4. If a group of users can form a coalition with the goal of artificially increasing the strength of a particular user through losing against that user on purpose, then that user is at an advantage **(CONCERN 4)**.

As we mentioned before, it would not be effective to address the first concern by ensuring that in every game, neither of the players is at an advantage (or

a disadvantage). Instead, the system has to adopt a non-local view on fairness and ensure that none of the players in the crowd is at an advantage (or a disadvantage) considering all played SGs. The second and third concerns can be addressed through either restricting the algorithm by which the system decides which SGs to be played, or through a more sophisticated approach to assess the user strength, or through both approaches. Anonymity can be used to defend against the fourth concern.

2.1.3 Evaluating User Contributions

Based on the outcome of an SG, we cannot safely assume that certain contributions are "correct". Therefore, the best we can do is to judge certain user contributions to be *potentially correct*. We consider contributions to be potentially correct if we have no reason to believe they are potentially incorrect.

By definition, the contributions of an SG loser are "Incorrect". Other reasons to believe that certain contributions are potentially incorrect include:

1. The position taken by the winner was not forced **(CONCERN 5)**.
2. There is a mechanism to discourage "cheating" (i.e. *knowingly* making "incorrect" contributions) either because their adversary is weak enough not to discover the "cheat", or to lose on purpose against their opponent **(CONCERN 6)**.

Anonymity can be used to discourage "cheating". It is also possible to hold the positions taken by users against themselves in future SGs.

2.1.4 Combining User Contributions

It is possible to collect the potentially correct contributions of all winners of SGs into a contribution database. The *crowd beliefs* about claims can be assessed from the contribution database. It is possible that "incorrect" contributions make it to the contribution database **(CONCERN 7)**. Therefore, it is necessary to have a mechanism to periodically clean the contribution database in order to enable more accurate assessment of the crowd beliefs.

Apart from estimating the crowd beliefs, SG losers get precise feedback on how they can improve their SG playing strategies. Furthermore, users can then build on the crowd beliefs. For example, suppose that the winners were mostly taking the verifier position on the claim $\forall k : divides(k, 3571) \Leftrightarrow k \in \{1, 3571\}$, then this likely-to-be-true claim can be used as a test case for factorization algorithms.

2.1.5 Recruiting and Retaining Users

Participating in an SG can provide users with an intrinsically rewarding experience. The exact intrinsic rewarding experience is user dependent. For example, some participants can find the act of game play against an adversary to be fun.

Others can enjoy the educational (or collaborative) nature of SGs that comes from the fact that the winner of an SG gives the loser very targeted feedback.

We believe that the following three factors that could enhance the intrinsically rewarding experience that SGs provide to users:

1. Choosing claims that both players find interesting **(CONCERN 8)**.
2. Allowing users to choose their positions on claims **(CONCERN 9)**.
3. Matching players with similar levels of strength **(CONCERN 10)**.

Neither intrinsic nor extrinsic reward is absolutely superior [2] [3]. However, most certainly, a crowd would have users that prefer both kinds of rewards. Therefore, it is still useful to include other encouragement and retention schemes **(CONCERN 11)** such as: instant gratification, providing ways to establish, measure, and show different qualities of the users, establishing competitions, and providing ownership situations [13].

2.2 Applications

Besides using an SG-based crowdsourcing system for solving computational problems, it is also possible to use it to for teaching, software development and formal science.

2.2.1 Teaching

The collaborative and self-evaluating nature of SGs is useful in teaching (especially MOOCs) where teaching other students help boost one's evaluation.

2.2.2 Software Development

The mandatory use of formal specification of claims and the orderly nature of the semantic games enables the system to be used as a crowdsourcing system for algorithms for computational problems as well. Because users can "automate themselves" as avatars (programs). The strongest avatars would have good algorithms either for generating tests for other avatars or solving a computational problem or both.

2.2.3 Formal Science

Although scientists in formal sciences are often interested in finding proofs to their claims, it remains helpful to test those claims first with the help of the crowd. Testing can provide them with useful insights. For example, testing can

[2] For example, consider using Amazon Mechanical Turk (AMT) to label all images indexed by Google. Would that be as cost effective as the ESP game? A second example is building the Wikipedia. Would it be as cost effective to build the Wikipedia using AMT?

[3] Extrinsic reward is believed to be superior in motivating automatic (motor) tasks, while intrinsic value would be superior in motivating intelligent (cognitive) tasks [25], [17], [15].

reveal a corner case where the claim does not hold. Reformulating the original claim to avoid such corner cases could be helpful in finding proofs [7]. It is worth mentioning that the phrase "formal science" is not limited to mathematics and logic. It also applies to scientific uses of formal simulation models.

3 Initial Investigation

To support our thesis, we designed and partially implemented [1] a proof of concept SG-based crowdsourcing system. Our system constitutes a redesign from scratch of the Scientific Community Game (SCG) [10], [9], [21] which has been evolving since 2007. Below, we describe our newly designed system and report on our experience of using earlier iterations of SCG for teaching.

3.1 System Overview

In a nutshell, our system uses first order logic to express claim families (See Appendix A for more details), and uses the semantic games of first order logic formulas defined by Hintikka's Game-Theoretic-Semantics [20] (See Appendix B for more details).

To ensure that claims are never forced on users our system uses labs. Labs define special interest groups of users. A lab is created by an owner (one kind of users) and consists of a family of claims. Scholars (another kind of users) choose to join the labs they find *interesting*. The system only allocates users to SGs of claims from the labs they joined. This enhances the users' experience while participating in SGs **(CONCERN 8)** and guarantees that users are never at a disadvantage regardless of the method used to chose the underlying claims for SGs **(CONCERN 1.a)**.

Rather than making scholars participate in SGs directly, the CIM in our system makes users participate in Contradiction-Agreement Games (CAGs). Although CAGs are composed of SGs, CAGs can be played by two players taking the same position on the underlying claims. This enhances the users' experience **(CONCERN 9)**. Furthermore, CAGs are specifically designed to provide fair evaluation **(CONCERN 1.b)** and to identify potentially correct contributions **(CONCERN 5)**. CAGs are described in Section 3.2. Currently, our system has a per-lab CIM. Lab owners are required to provide their CIM mechanisms taking into account to match scholars with close enough strength. This is critical to enhance the users' experience **(CONCERN 10)** and fairness **(CONCERN 3)**.

Our system uses an algorithm to evaluate the users' strength as fairly as possible. Our algorithm is designed to address the fairness concerns **(CONCERN 2,3)**. The algorithm is described in Section 3.3. To estimate crowd beliefs, our system uses a simple formula that is presented in Section 3.4. To discourage "cheating" **(CONCERN 4,6)**, our system relies on anonymity. Currently, our system does not provide a mechanism for cleaning the contributions database

Game	forced	winner	payoff (p_1, p_2)	potentially correct contribution
Agreement T1	p_2	p_1	(0, 0)	p_1
	p_2	p_2	(0, 1)	–
Agreement T2	p_1	p_1	(1, 0)	–
	p_1	p_2	(0, 0)	p_2
Contradiction	–	p_1	(1, 0)	p_1
	–	p_2	(0, 1)	p_2

Table 1: The Contradiction-Agreement Game

(CONCERN 7) nor any encouragement and retention schemes **(CONCERN 11)** other than the fun that scholars get from participating in SGs.

3.2 The Contradiction-Agreement Game

CAGs remove the restriction that scholars must take contradictory positions on claims. In case scholars take contradictory positions, CAG reduces to one SG. Otherwise, CAG reduces to two testing SGs. In a test SG, one of the scholars, the tester, is forced to take the opposite position of the position it chose. The two scholars switch their testing roles between the two games. Even though the tester is forced to take a particular position, CAG-based evaluation remains fair. It also remains possible to get potentially correct contributions out of the testing games when the winner is not the forced tester.

SGs with forced scholars can cause unfairness in two different ways:

1. Winning against a forced scholar is not the same as winning against an unforced scholar. Giving both winners a point for winning would be unfair.

2. The forced scholar is at a disadvantage.

To overcome these two problems, we adopt the rule that the scholar winning an SG *scores* a point only if its adversary is not forced. Although, this solves the two problems, it, oddly enough, puts the winner at a disadvantage because it has no chance of *scoring* a point. Luckily, considering both test games together, the evaluation (i.e. payoff) is fair because both scholars have an equal chance of scoring. Furthermore, scholars remain properly incentivised to win under the payoff. This is important to ensure the fairness of user evaluation as well as the potential correctness of the contributions of the unforced winners. Our readers can verify these properties by inspecting Table 1 which summarizes CAGs. The columns of the table indicate the name of the SG being played, the forced scholar (if any), the SG winner, and whether the contribution of the winner is potentially correct (assuming that "cheating" is somehow discouraged).

3.2.1 CAG Desirable Properties

CAG encourages innovation because forced scholars can score while their adversary cannot. This provides an incentive for forced players to win SGs even though they are forced to take positions that are often contradictory to their own intuition as well as to the crowd beliefs. Also, CAGs ensure that some form of progress is taking place either as an update to the player scores or that a potentially correct contribution has been made. Furthermore, in the first case, the loser is receiving back targeted feedback and in the second case, the community benefits from the potentially correct contribution.

3.3 Evaluating User Strength

We devised an algorithm to evaluate user strength based on CAG scores. The algorithm weighs the scores by the strength of the adversary and calculates the strength of the scholar as the ratio of wins over the sum of wins and losses in order to to even out the difference in the number of played CAGs **(CONCERN 2)** as well as the difference in the strength of adversaries **(CONCERN 3)**.

Informally, the algorithm starts with an estimate of 1 for the strength of all players. Then it computes the weighted wins and losses for each player based on the payoffs and the strength of their adversaries. Then it computes strength as the fraction of weighted wins divided by the sum of weighted wins and losses. The last two steps are iterated to a fixpoint.

Formally, we denote the sum of payoffs that scholar S_1 gets from scholar S_2 by $\mathit{Payoff}(S_1, S_2)$. The strength of user S is denoted by $Str(S)$. The algorithm is given by:

$$
\begin{aligned}
Str^{(-1)}(S_i) &= 1 \\
Wins^{(k)}(S_i) &= \sum \mathit{Payoff}(S_i, S_j) * Str^{(k-1)}(S_j) \\
Losses^{(k)}(S_i) &= \sum \mathit{Payoff}(S_j, S_i) * (1 - Str^{(k-1)}(S_j)) \\
Total^{(k)}(S_i) &= Wins^{(k)}(S_i) + Losses^{(k)}(S_i) \\
Str^{(k)}(S_i) &= \begin{cases} Wins^{(k)}(S_i)/Total^{(k)}(S_i), & \text{if } Total^{(k)} \neq 0 \\ 0.5, & \text{otherwise.} \end{cases}
\end{aligned}
$$

Ideally, we would like the strengths produced by the algorithm to be *consistent* with the payoffs (i.e. $\forall S_1, S_2 : \mathit{Payoff}(S_1, S_2) \geq \mathit{Payoff}(S_2, S_1) \Rightarrow Str(S_1) \geq Str(S_2)$). However, the relation $R(S_1, S_2) = \mathit{Payoff}(S_1, S_2) \geq \mathit{Payoff}(S_2, S_1)$ is not necessarily transitive while the relation $Q(S_1, S_2) = Str(S_1) \geq Str(S_2)$ is. However, we conjecture that the strengths produced by our algorithm minimize such inconsistencies.

However, the the algorithm possesses the following weaker soundness properties:

1. A scholar S_i that beats the score of another scholar S_j on their mutual games as well as on games with all other scholars S_k will have a higher strength. $\forall i, j \mathit{Payoff}(S_i, S_j) > \mathit{Payoff}(S_j, S_i) \wedge \forall k \neq i, j : \mathit{Payoff}(S_i, S_k) \geq \mathit{Payoff}(S_J, S_k) \wedge \mathit{Payoff}(S_j, S_k) \leq \mathit{Payoff}(S_i, S_k) \Rightarrow \mathit{Str}(S_i) \geq \mathit{Str}(S_j)$.

2. A scholar that only won(lost) games will have a strength of 1(0). Formally, $\forall i \forall j \mathit{Payoff}(S_i, S_j) = 0 \wedge \exists j \mathit{Payoff}(S_j, S_i) > 0 \Rightarrow \mathit{Str}(S_i) = 0$, and $\forall i \forall j \mathit{Payoff}(S_j, S_i) = 0 \wedge \exists j \mathit{Payoff}(S_i, S_j) > 0 \Rightarrow \mathit{Str}(S_i) = 1$. A scholar that has not won or lost any games will have a strength of 0.5. Formally, $\forall i \forall j \mathit{Payoff}(S_j, S_i) = 0 \wedge \mathit{Payoff}(S_i, S_j) = 0 \Rightarrow \mathit{Str}(S_i) = 0.5$.

3.4 Evaluating Crowd Beliefs

We consider the positions taken by non-forced CAG winners to be providing the community with an evidence that these positions are correct. We take the strength of the losing user as the weight of such evidence. For each claim c we let c_T be the sum of the weights of all evidences that c is true, c_F be the sum of the weights of all evidences that c is false. The believed likelihood that c is true is $C_T/(C_T + C_F)$. Similarly, the believed likelihood that c is false is $C_F/(C_T + C_F)$.

3.5 Experience with SCG

We report on our experience using SCG in teaching algorithms classes [2]. The most successful course (using [19] as textbook) was in Spring 2012 where the interaction through the SCG encouraged the students to solve difficult problems. Almost all homework problems were defined through labs and the students posted both their exploratory and reformatory actions [22] [4] on Piazza [3]. We used a multi player version of the SCG binary game which created a bit of an information overload. Sticking to binary games would have been better but requires splitting the students into pairs. The informal use of the SCG through Piazza proved successful. All actions were expressed in JSON which allowed the students to use a wide variety of programming languages to implement their algorithms.

The students collaboratively solved several problems such as the problem of finding the worst-case inputs for the Gale-Shapely stable matching algorithm.

We do not believe that, without the SCG, the students would have created the same impressive results. The SCG effectively focuses the scientific discourse on the problem to be solved.

The SCG proved to be adaptive to the skills of the students. A few good students in a class become effective teachers for the rest thanks to the SCG mechanism.

[4] Choosing a claim and a position are exploratory actions, supporting actions are performatory actions.

4 Proposed Further Investigation

Our proposed work includes further development to the current system, its underlying model, as well as to evaluate our system.

4.1 Model Development

4.1.1 Claim Family Relations and Meta Labs

Relations computational problems can be used to *test* implementations of their solution algorithms. Reduction is an important kind of relation between computational problems that can be used to *prove* certain impossibility results as well as to enable the implementation of one computational problem to *reuse* the implementation of another computational problem.

In our system, these relations can be expressed as claims between claim families specifying computational problems. For example, consider the following two claim families:

1. *Size of minimum graph basis*: a basis of a directed graph G is defined as set of nodes such that any node in the graph is reachable from some node in the basis. Formally, $MinBasisSize(G \in Digraphs, n \in \mathbb{N}) = BasisSize(G, n) \wedge \forall k \; s.t. \; k < n : \neg BasisSize(G, k)$ where $BasisSize(G \in Digraphs, n \in \mathbb{N}) = \exists s \in \mathcal{P}(nodes(G)) \; s.t. \; |s| = n \; : \forall m \in nodes(G) \; \exists p \in paths(G) : first(p) = m \wedge last(p) \in s$.

2. *Number of source nodes of a DAG*: a source node is a node with no incoming edges. Formally, $\#src(D \in DAGs, m \in \mathbb{N}) = \exists s \in \mathcal{P}(nodes(D)) \; s.t. \; |s| = m \; : \forall v \in nodes(D) : inDegree(v) = 0 \Leftrightarrow v \in s$.

The relation between the two claim families $MinBasisSize(G \in Digraphs, n \in \mathbb{N})$ and $\#src(D \in DAGs, m \in \mathbb{N})$ can be described by $\forall G \in Digraphs, n \in \mathbb{N} \; : MinBasisSize(G, n) = \#src(SCCG(G), n)$ where $SCCG$ refers to Tarjan's the Strongly Connected Component Graph algorithm.

Like other claims, claims about relations between claim families can be studied in a regular lab in our system. However, we see a potential to further utilize these claims to cross check crowd beliefs across labs and to translate user contributions across labs. To harness this potential, we propose to add meta labs to our system. More specifically, we propose to answer the two following questions:

1. How can our system further utilize relations between claim families beyond regular claims?

2. How to express meta labs so that it is possible to further utilize them in an automated way?

4.1.2 Generalized Claims

Users can lose SGs involving optimization problems even if their solutions can be *almost* optimal. For example, consider the following claim:

$$\forall p \in Problem : \exists s \in Solution : \forall t \in Solution : better(quality(s,p), quality(t,p))$$

It is enough for the falsifier to provide a *slightly* better solution to win. As remedy, it is possible to bias the situation towards the verifier by requiring the falsifier to provide at solution that is at well better than the solution provided by the verifier in order to win. The following claim illustrates this solution:

$$\forall p \in Problem : \exists s \in Solution : \forall t \in Solution : within10\%(quality(s,p), quality(t,p))$$

It is also possible to generalize the claims such that the larger the quality gap is, the more of a payoff the winner gets. For example, assuming the *distance* function returns a number between -1 and 1, the following generalized claim illustrates this solution:

$$\forall p \in Problem : \exists s \in Solution : \forall t \in Solution : distance(quality(s,p), quality(t,p))$$

We propose to develop a systematic approach for computing the payoff in SGs for generalized claims.

4.2 System Development

We propose to turn the current implementation [1] into a web based application. We also propose to further develop the claim language and the CIM and the encouragement and retention scheme.

4.2.1 Claim Language

There are certain game related concerns that cannot be expressed in the current claim language. Furthermore, the current language is not as user friendly as it could be. To overcome these two problems, we propose to make the following enhancements to the claim language:

1. make the claim language support second order logical sentences. This enables the claim language to express properties about the resource consumption of algorithms. For example, $AlgoRunTime(c, n_{min}, n_{max}) = \exists a \in Algo : \forall i \in Input\ s.t.\ n_{min} \leq size(i) \leq n_{max} : correct(i, a(i)) \wedge RunTime(a(i)) <= c * size(i)$.
   Second order logical sentences can also express the dependence (or independence) of atoms through skolem functions as well. Other approaches to express the dependence concerns is through either the dependence friendly logic or the independence friendly logic [27].

2. add a *let* binder for efficiency. For example, to avoid computing $a(i)$ twice in *AlgoRuntime*.

3. add syntactic forms, in addition to *Formula*, to provide a more user friendly support of different kinds of computational problems (such as search, optimization, counting problems). For example, to enable users to write: $sat(f) = \max_J csat(f, J)$, instead of: $sat(f, x) = \exists J \; s.t. \; csat(f, J) = x : \forall H : csat(f, H) \leq csat(f, J)$

4. add an abstraction facility.

4.2.2 Crowd Interaction Mechanism

We propose to implement the following CIM. Lab owners establish Swiss-style CAG tournaments between scholars in the lab in order to drive interactions in the lab. Swiss-style tournaments have the property of matching players with similar strength and therefore enhancing the users' experience **(CONCERN 10)** as well as fairness **(CONCERN 3)**. Claims can be chosen by one of the following approaches:

1. *CAG matches*: CAG matches consist of an even number of CAGs. Each scholar chooses the claim for exactly half of the CAGs. Claims must be chosen from the lab's claim family. A generalization of this approach is to play a cut-and-choose game [14] where in each round, one players chooses a set of claims (a cut) then the adversary chooses a claim from the set.

2. *Owner dictated*: the lab owner provides an algorithm for selecting claims to achieve a particular purpose. For example, if the purpose is to clean the contribution database, then the algorithm would select claims underlying scholar contributions in the contribution database. The purpose could also to solve a particular subset of open problems or to solve a computational problem in a particular approach, delegating subproblems to the crowd. For example, the purpose could be to *plot* the relationship between a particular claim family parameter and the correctness of the claim.

3. *Battleship style*: use a claim that both scholars had previously contributed a position on.

A distinctive feature of this CIM is that scholars never choose their adversaries. This is important to discourage "cheating" **(CONCERN 4,6)**. A second feature is that CIM *memoizes* winning positions taken by scholars and never asks scholars to provide these positions in subsequent CAGs until scholars fail to defend these positions. The contribution database plays the role of the cache for winning positions. This is important to discourage "cheating" **(CONCERN 6)**. It is also important that the CIM allows scholars to revise their previously established contributions to avoid losing future CAGs

4.2.3 Encouragement and Retention Scheme

We suppose that scholars will aspire to have the highest scores on meaningful performance measures. The system can establish the scores for players and

provide few different views, such as a leaderboard, for scholars to encourage score based competition. In addition to strength, we propose to develop the following complementary measures:

1. *Breakthrough contribution* : When required to do so, scholars might provide well known claims that they know how to defend. The purpose of developing a measure for breakthrough contributions is to encourage scholars to propose new claims and take positions opposing to the crowd beliefs.

2. *Learning* : Learning is an indirect contribution of scholars. We propose to assess learning through the change in scholar's strength as well as through scholar's revisions to its own established contributions.

3. *Crowd preference* : Scholars might be able to spot certain attractive properties of a particular contribution. The idea is to enable scholars to "like" contributions and essentially count the "likes" the contributions of a particular scholar gets.

Another potential encouragement and retention scheme that we want to explore is to have an underlying theme where scholars are represented by customizable virtual avatars. This enhances the engagement as scholars can become invested in customizing their avatars besides it makes it easier for scholars to be embodied in CAGs by their avatar.

4.3 Evaluation

We propose to conduct a two part evaluation of effectiveness of our system in leveraging the problem solving ability of the crowd. The first part consists of evaluating the quality of the algorithms produced by the crowd to solve non-trivial computational problems. We propose to compare those algorithms to the best known algorithms. Examples include the max cut problem and the highest safe rung problems. The second part consists of comparing the quality of the algorithms produced by the crowd through our system to algorithms produced through traditional crowdsourcing competitions. Examples include the genome-sequencing-problem [4].

We propose to also use our crowdsourcing system to evaluate a number of its components and their properties.

5 Plan

Our plan is to spend about 3 months on developing the model and the system. During these 3 months we plan to submit a paper about the developed model and system either to the First AAAI Conference on Human Computation and Crowdsourcing [5] or to Ninth Annual AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment [6]. Then to spend another 3 months to do the evaluation and write the dissertation.

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Appendix A Claim Language

A claim is an interpreted statement in first order predicate logic. A claim consists of an underlying model M, a predicate formula ϕ potentially containing free variables, an assignment g for the free variables in ϕ.

A `Formula` is either a simple `Predicate`, a `Compound` formula, a `Negated` formula, or a `Quantified` formula. A `Compound` formula consists of two subformulas, `left` and `right` and a `Connective` which is either an `And` or an `Or` connective. A `Quantified` formula consists of a `Quantification` and a subformula. A `Quantification` consists of a `Quantifier`, two `ident`ifiers representing the quantified variable name and type, and an optional `Predicate` further restricting the values the quantified variable can take. A `Quantifier` can be either a `ForAll`, an `Exists`, or `Free` which we use to declare free variables in a formula. Figure 1 shows the grammar for a formula expressed using the class dictionary notation [11].

```
Formula = Predicate | Compound | Negated | Quantified.
Predicate = <name> ident "(" <args> CommaList(ident) ")".
Compound = "(" <left> Formula
          <connective> Connective
          <right> Formula ")".
Negated = "(" "not" <formula> Formula ")".
Connective = And | Or.
And = "and".
Or = "or".

Quantified = <quantification> Quantification <formula> Formula
    .
Quantification = "(" <quantifier> Quantifier
                 <var> ident
                 "in" <type> ident
                 <qPred> Option(QuantificationPredicate) ")".
QuantificationPredicate = "where" <pred> Predicate.
Quantifier = ForAll | Exists | Free.
ForAll = "forall".
Exists = "exists".
Free = "free".
```

Figure 1: Formula Language

Appendix B Semantic Games

Given a claim `c` and two scholars, a verifier *ver* and a falsifier fal. Let M be the underlying model of `c`, let ϕ be the formula and g be `c`'s assignment to the free variables in ϕ. We define the semantic game of *ver* and fal centered around `c`

`SG(c,`ver`, `fal`)` to be $G(\phi, M, g, ver, fal)$ which is a two-player, zero-sum game defined as follows:

1. If $\phi = R(t_1, ..., t_n)$ and $M, g \models R(t_1, ..., t_n)$, ver wins; otherwise fal wins.
2. If $\phi = !\psi$, the rest of the game is as in $G(\psi, M, g, fal, ver)$.
3. If $\phi = (\psi \wedge \chi)$, fal chooses $\theta \in \{\psi, \chi\}$ and the rest of the game is as in $G(\theta, M, g, ver, fal)$.
4. If $\phi = (\psi \vee \chi)$, ver chooses $\theta \in \{\psi, \chi\}$ and the rest of the game is as in $G(\theta, M, g, ver, fal)$.
5. If $\phi = (\forall x : p(x))\psi$, fal chooses an element a from M such that $p(a)$ holds, and the rest of the game is as in $G(\psi, M, g[x/a], ver, fal)$. If fal fails to do so, it loses.
6. If $\phi = (\exists x : p(x))\psi$, ver chooses an element a from M such that $p(a)$ holds, and the rest of the game is as in $G(\psi, M, g[x/a], ver, fal)$. If ver fails to do so, it loses.

The definition of G is adopted from the Game Theoretic Semantics (GTS) of Hintikka [20], [26]. We slightly modified Hintikka's original definition to handle the quantification predicate in our language.