Altruism in Atomic Congestion Games

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Abstract. This paper studies the effects of introducing altruistic agents into atomic congestion games. Altruistic behavior is modeled by a trade-off between selfish and social objectives. In particular, we assume agents optimize a linear combination of personal delay of a strategy and the resulting social cost. Stable states are the Nash equilibria of these games, and we examine their existence and the convergence of sequential best-response dynamics. For symmetric singleton games with arbitrary delay functions we provide a polynomial time algorithm to decide existence for symmetric singleton games. Our algorithm can be extended to compute best and worst Nash equilibria if they exist. For more general congestion games existence becomes NP-hard to decide, even for symmetric network games with quadratic delay functions. Perhaps surprisingly, if all delay functions are linear, there exists a Nash equilibrium and any better-response dynamics converges. In addition, we consider a scenario in which a central altruistic institution can motivate agents to act altruistically. We provide constructive and hardness results for finding the minimum number of altruists to stabilize an optimal congestion profile and more general mechanisms to incentivize agents to adopt favorable behavior.

1 Introduction

Algorithmic game theory has been focused on game-theoretic models for a variety of important applications in the Internet. A fundamental assumption in these games, however, is that all agents are *selfish*. Their goals are restricted to optimizing their direct personal benefit, e.g. their personal delay in a routing game. The assumption of selfishness in the preferences of agents is found in the vast majority of present work on economic aspects of the Internet. However, this assumption has been repeatedly questioned by economists and psychologists. In experiments it has been observed that participant behavior can be quite complex and contradictive to selfishness [15,16]. Various explanations have been given for this phenomenon, e.g. senses of fairness [7], reciprocity among agents [10], or spite and altruism [16,5].

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Prominent developments in the Internet like Wikipedia, open source software development, or Web 2.0 applications involve or explicitly rely on voluntary participation and contributions towards a joint project without direct personal benefit. These examples display forms of *altruism*, in which agents accept certain personal burdens (e.g. by investing time, attention, and money) to improve a common outcome. While malicious behavior has been considered recently for instance in nonatomic routing [14,3,4], virus incoulation [18], or bayesian congestion games [8], a deeper analysis of the effects of altruistic agents on competitive dynamics in algorithmic game theory is still missing.

We consider and analyze a model of altruism inspired by Ledyard [15, p. 154], and recently studied for non-atomic routing games by Chen and Kempe [4]. Each agent i is assumed to be partly selfish and partly altruistic. She optimizes a linear combination of personal cost and social cost, given by the sum of cost values of all agents. The strength of altruism of each agent i is captured by her *altruism level* $\beta_i \in [0, 1]$, where $\beta_i = 0$ results in a purely selfish and $\beta_i = 1$ in a purely altruistic agent.

Chen and Kempe [4] proved that in non-atomic routing games Nash equilibria are always guaranteed to exist and analyzed the price of anarchy for parallel link networks. In our paper, we conduct the first study of altruistic agents in atomic congestion games, a well-studied model for resource sharing. Congestion games received a lot of attention recently, mostly because of the intuitive formulation and their appealing analytical properties. In particular, they always possess a pure Nash equilibrium and every sequential better-response dynamics converges. As one might expect, the presence of altruists can significantly alter the convergence and existence of pure Nash equilibria. After a formal definition of *congestion games with altruists* in Section 2, we concentrate on pure equilibria and leave a study of mixed Nash equilibria for future work. Our results are as follows.

We study singleton games in Section 3, in which every strategy consists of a single resource. In symmetric games with a constant number of different altruism levels, we can decide in polynomial time if a Nash equilibrium exists. Our algorithm can be adapted to compute the Nash equilibrium with best and worst social cost if it exists, for any agent population with a constant number of different altruism levels. For *asymmetric singleton games*, in which strategy spaces of agents differ, deciding the existence of Nash equilibria becomes NP-hard. For the important subclass of convex delay functions, i.e., linear and superlinear functions, previous results imply that for any agent population a Nash equilibrium exists and can be computed in polynomial time. In contrast, we show in Section 4 that convexity of delay functions is not sufficient for more general games. Even for *symmetric network games*, in which strategies represent paths through a network, quadratic delay functions and pure altruists, Nash equilibria can be absent and deciding their existence is NP-hard. Perhaps surprisingly, if all delay functions are *linear*, the game is a potential game.

In Section 5 we consider a slightly more coordinated scenario, in which there is a central institution that can convince agents to act altruistically. In this context a natural question is how many altruists are required to stabilize a social optimum. This has been considered under the name "price of optimum" in [13] for Stackelberg routing in nonatomic congestion games. We consider two measures - an *optimal stability threshold*, which is the minimum number of altruists such that there is *any* optimal Nash equilibrium, and an *optimal anarchy threshold*, which asks for the minimum number of altruists such that *every* Nash equilibrium is optimal. For symmetric singleton games, we adapt our algorithm for computing Nash equilibria to determine both thresholds in polynomial time. The optimal anarchy threshold might not be well-defined even for singleton games, because there are suboptimal Nash equilibria even if all agents are pure altruists. In contrast, we adapt the idea of the optimal stability threshold to a very general scenario, in which each agent has a personalized *stability cost* for accepting a strategy under the given congestions. We provide a truthful mechanism to determine an allocation of agents to strategies with minimum total stability cost. Unfortunately, such a general result is restricted to the case of singleton games. Even for symmetric network games on series-parallel graphs, we show that the problem of determining the optimal stability threshold is NP-hard. Our reduction also yields inapproximability within any finite factor. This resolves an open problem raised in [12] on computing the "price of optimum" in atomic congestion games.

Some proofs have been omitted due to spacial constraints, they will be given in a full version of this paper.

2 Model and Initial Results

We consider congestion games with altruists. A *congestion game with altruists* G is given by a set N of n agents and a set E of m resources. Each agent i has a set $\mathcal{S}_i \subseteq 2^E$ of strategies. In a *singleton* congestion game each agent has only singleton strategies $\mathcal{S}_i \subseteq E$. A vector of strategies $S = (S_1, \ldots, S_n)$ is called a *state*. For a state we denote by n_e the congestion, i.e. the number of agents using a resource e in their strategy. Each resource e has a *latency* or *delay* function $d_e(n_e)$, and the *delay for an agent i* playing S_i in state S is $d_i(S) = \sum_{e \in S_i} d_e(n_e)$. The *social cost* of a state is the total delay of all agents $c(S) = \sum_{i \in N} \sum_{e \in S_i} d_e(n_e) = \sum_{e \in E} n_e d_e(n_e)$. Each agent i has an *altruism level* of $\beta_i \in [0,1]$, and her *individual cost* is $c_i(S) = \beta_i c(S) + (1-\beta_i) d_i(S)$. We call an agent i an *egoist* if $\beta_i = 0$ and a *β_i-altruist* otherwise. A *(pure) altruist* has $\beta_i = 1$, a *(pure) egoist* has $\beta_i = 0$. A game *G with only pure altruists and egoists* is a game, in which $\beta_i \in \{0,1\}$ for all $i \in N$. A game G is said to have *β-uniform* altruists if $\beta_i = \beta \in [0,1]$ for every agent $i \in N$. A (pure) *Nash equilibrium* is a state S, in which no agent i can unilaterally decrease her individual cost by unilaterally changing her strategy. We exclusively consider pure equilibria in this paper.

If all agents are egoists, the game is a regular congestion game, which has an exact potential function $\Phi(S) = \sum_{e \in E} \sum_{x=1}^{n_e} d_e(x)$ [20]. Thus, existence of Nash equilibria and convergence of iterative better-response dynamics are guaranteed.

Obviously, if all agents are altruists, Nash equilibria correspond to local optima of the social cost function c with respect to a local neighborhood consisting of single player strategy changes. Hence, existence and convergence are also guaranteed. This directly implies the same properties for β-uniform games, in which an exact potential function is $\Phi_\beta(S) = (1-\beta)\Phi(S) + \beta c(S)$. In general, however, Nash equilibria might not exist.

Observation 1. *There are symmetric singleton congestion games with only pure altruists and egoists without a Nash equilibrium.*

Example 2. Consider a game with two resources e and f, three egoists and one (pure) altruist. The delay functions are $d_e(x) = d_f(x)$ with $d_e(1) = 4$, $d_e(2) = 8$, $d_e(3) = 9$, and $d_e(4) = 11$. One can easily check that this game does not posses a Nash equilibrium.

Our interest is thus to characterize the games that have Nash equilibria. Towards this end we observe that an altruistic congestion game can be cast as a congestion game with player-specific latency functions [17]. In such a game the delay of resource e to player i depends on the congestion and on the player, i.e., $c_i(S) = \sum_{e\in S_i} d_e(n_e, i)$. To embed our games within this framework, we consider a game with only pure altruists and egoists for simplicity. An altruist moves from S_i to S_i' if the decrease in total delay $n_e d_e(n_e)$ on the resources $e \in S_i - S_i'$ she is leaving exceeds the increase on resources $e \in S_i' - S_i$ she is migrating to. Hence, altruists can be seen as myopic selfish agents with $c_i(S) = d_i'(S) = \sum_{e\in S_i} d_e'(n_e)$ with $d_e'(n_e) = n_e d_e(n_e) - (n_e-1)d_e(n_e-1)$, for $n_e > 0$. We set $d_e'(0) = 0$. Naturally, a β_i-altruist corresponds to a selfish agent with player-specific function $c_i(S) = (1-\beta_i)d_i(S) + \beta_i d_i'(S)$. Thus, our games can be embedded into the class of player-specific congestion games. For some classes of such games it is known that Nash equilibria always exist. In particular, non-existence in Example 2 is due to the fact that the individual delay function for the altruist is not monotone. Monotonicity holds, in particular, if delay functions are convex. In this case, it is known that for matroid games, in which the strategy space of each agent is a matroid, existence of a Nash equilibrium is guaranteed [2].

Corollary 3. *[17,2] For any matroid congestion game with altruists and convex delay functions a Nash equilibrium exists and can be computed in polynomial time.*

3 Singleton Congestion Games

In the previous section we have seen that there are symmetric singleton congestion games with only pure altruists and egoists with and without Nash equilibria. For this class of games we can decide the existence of Nash equilibria in polynomial time. In addition, we can compute a Nash equilibrium with minimum and maximum social cost if they exist.

Theorem 4. *For symmetric singleton games with only pure altruists and egoists there is a polynomial time algorithm to decide if a Nash equilibrium exists and to compute the best and the worst Nash equilibrium.*

The proof relies on the fact that the game is symmetric and the number of resources is polynomial. This allows us to characterize a Nash equilibrium using certain maximum and minimum values for the delays of each resource. Similar to [11] we can implicitly enumerate all states that can be a Nash equilibrium using dynamic programming. The approach can be extended to a constant number k of different altruism levels. In this more general scenario we choose the delay parameters for each level of altruists.

Corollary 5. *For symmetric singleton games with altruists and a constant number of different altruism levels, there is a polynomial time algorithm to decide if a Nash equilibrium exists and to compute the best and the worst Nash equilibrium.*

As a byproduct, our approach also allows us to compute a social optimum state in polynomial time. We simply assume all agents to be pure altruists and compute the best Nash equilibrium.

Corollary 6. *For symmetric singleton congestion games a social optimum state can be obtained in polynomial time.*

In case of asymmetric games, however, deciding the existence of Nash equilibria becomes significantly harder.

Theorem 7. *It is* NP*-hard to decide if a singleton congestion game with only pure altruists and egoists has a Nash equilibrium if G is asymmetric and has concave delay functions.*

Proof. We reduce from 3SAT. Given a formula φ, we construct a congestion game G_φ that has a Nash equilibrium if and only if φ is satisfiable. Let $x_1, \ldots, x_n$ denote the variables and $c_1, \ldots, c_m$ the clauses of a formula φ. Without loss of generality [21], we assume each variable appears at most twice positively and at most twice negatively.

For each variable x_i there is a selfish agent X_i that chooses one of the resources $e^1_{x_i}$, $e^0_{x_i}$, or e_0. The resources $e^1_{x_i}$ and $e^0_{x_i}$ have the delay function $9x$ and resource e_0 has the delay function $7x + 3$. For each clause c_j, there is a selfish agent C_j who can choose one of the following three resources. For every positive literal x_i in c_j he may choose $e^0_{x_i}$. For every negated literal $\bar{x}_i$ in c_j he may choose $e^1_{x_i}$. Note that there is a stable configuration with no variable agent on e_0 if and only if there is a satisfiable assignment for φ. Additionally, there are three selfish agents u_1, u_2, and u_3 who can choose e_1 or e_2. Each of the resources e_1 and e_2 has delay 4 if used by one agent, delay 8 if used by two agents and delay 9 otherwise. The only pure altruist u_0 chooses between e_1, e_2, and e_0. Note that the altruist chooses e_1, e_2 if one of the variable agents is on e_0.

If φ is satisfiable by a bitvector $(x^*_1, \ldots, x^*_n)$, a stable solution for G_φ can be obtained by placing each variable agent x_i on $e^{x^*_i}_{x_i}$. Since $(x^*_1, \ldots, x^*_n)$ satisfies φ

there is one resource for each clause agent that is not used by a variable agent. Thus, we can place each clause agent on this resource, which he then shares with at most one other clause agent. Let the altruist u_0 use e_0 and u_1 and u_2 choose e_1 and u_3 choose e_2. It is easy to check that this is a Nash equilibrium.

If φ is unsatisfiable, there is no stable solution. To prove this it suffices to show that one of the variable agents prefers e_0. In that case the altruist never chooses e_0 and the agent $u_0, \ldots, u_3$ play the sub game of Example 2. For the purpose of contradiction assume that φ is not satisfiable but there is a stable solution in which no variable wants to choose e_0. This implies that there is no other agent, i.e. a clause agent, on a resource that is used by a variable agent. However, if all clause agents are on a resource without a variable agent we can derive a corresponding bit assignment which, by construction, satisfies φ. Therefore, G_φ has a stable solution if and only if φ is satisfiable. □

4 General Games

For any singleton game G with altruists and convex delay functions a Nash equilibrium always exists. For more general network structures, we show that convexity of delay functions is not sufficient. In particular, this holds even for games with only pure altruists and egoists in the case in which almost all delay functions are linear of the form $d_e(x) = a_e x$, except for two edges, which have quadratic delay functions $d_e(x) = a_e x^2$. For simplicity, we use some edges with non-convex constant delay b_e. We can replace these edges by sufficiently many parallel edges with delay $b_e x$. This transformation is of polynomial size and yields an equivalent game with only convex delays.

Theorem 8. *It is* NP*-hard to decide if a symmetric network congestion game with only pure altruists and egoists and quadratic delay functions has a Nash equilibrium.*

Proof. We first reduce from 3SAT to asymmetric congestion games. Again, we assume each variable appears at most twice positively and at most twice negatively. In a second step, we show that the resulting congestion games can be turned into symmetric games while preserving all necessary properties.

Our reduction is similar to the construction that we used in the proof of Theorem 7. The structure of the resulting network congestion game G_Φ is depicted in Figure 1. Table 1 lists the delay functions of the edges. Edges that are not listed there have delay of 0. Due to space limitations we only outline the structure of our construction. The complete proof will appear in the full version.

Each agent X_i chooses one of three paths from his source node s_{x_i} to his target node t'. Each clause agent C_j uses a path from s_{c_j} to t' and uses one of the three edges as described in the proof of Theorem 7. That is, for each positive literal x_i in c_j he may choose a path that includes the edge $e^0_{x_i}$. For every negated literal $\bar{x}_i$ in c_j he may choose a path that contains the edge $e^1_{x_i}$. There is a selfish agent u_1 that chooses a path from s_1 to t' and two selfish agents u_2 and u_3 that

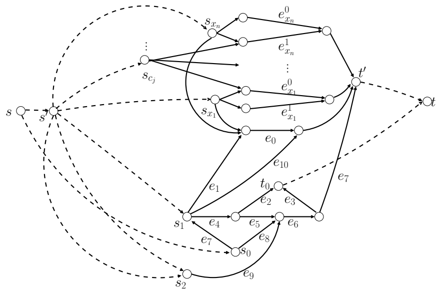

Fig. 1. The structure of the network of G_Φ (solid edges only) and G'_Φ

Table 1. The delay functions on the edges of G_Φ and G'_Φ

Edge	delay function
e_0	$7x+3$
e_1	2
e_2	17
e_4	$2.4x^2$
e_6	x^2
e_{10}	18.5
$e^1_{x_i}, e^1_{x_i}$	$9x$
$(s, s_{x_i})\ \forall 1 \le i \le n$	Mx
$(s, s_{c_j})\ \forall 1 \le j \le m$	Mx
(s, s_1), (s, s_2), (s, s')	Mx
(s, s_0)	$(n+m+5)M$
(t_0, t)	$(n+m+5)M$
(t', t)	Mx

allocate the path from s_2 to t'. Finally, one altruistic agent u_0 chooses a path from s_0 to t_0.

The asymmetric network congestion game G_Φ can be turned into a symmetric congestion game G'_Φ. We add a new source node s, a new target node t and a node s' to the network and connect them to G_Φ as depicted by the dashed edges in Figure 1. Note that M is an integer that is larger than the sum of possible delay values in G_Φ. $\square$

Perhaps surprisingly, if *every* delay function is linear $d_e(x) = a_e x + b_e$, then an elegant combination of the Rosenthal potential and the social cost function yields a potential for arbitrary β_i-altruists. Hence, existence of Nash equilibria and convergence of sequential better-response dynamics is always guaranteed. The proof is carefully constructed for altruists, as for congestion games with general player-specific linear latency functions a potential does not exist [9]. We only consider delays $d_e(x) = a_e x$ without offset b_e, but as noted earlier, this is not a restriction.

Theorem 9. *For any congestion game with altruists and linear delay functions there is always a Nash equilibrium and sequential better-response dynamics converges.*

Proof. The theorem follows from the existence of a weighted potential Φ that decreases during every improvement step of any agent i with altruism level β_i.

$$\Phi(S) = \sum_{e\in E}\sum_{j=1}^{n_e} a_e j + \sum_{e\in E} a_e n_e^2 - \sum_{i=1}^{n}\sum_{e\in S_i} \frac{2\beta_i - 1}{\beta_i + 1} a_e$$

Consider a state S and an improving strategy change of an agent i from S_i to S'_i resulting in a strategy profile S'. We show that Φ decreases. For the sake of clarity and brevity we set $\Delta_N = \sum_{e\in S_i\setminus S'_i} a_e n_e - \sum_{e\in S'_i\setminus S_i} a_e(n_e+1)$ and

$\Delta_C = \sum_{e \in S_i \setminus S_i'} (2a_e n_e - a_e) - \sum_{e \in S_i' \setminus S_i} (2a_e n_e + a_e)$. Note that an improving strategy change requires $(1-\beta)\,\Delta_N + \beta \Delta_C > 0$.

$$\Phi(S) - \Phi(S') = \Delta_N + \Delta_C - \sum_{e \in S_i \setminus S_i'} \frac{2\beta_i - 1}{\beta_i + 1} a_e + \sum_{e \in S_i' \setminus S_i} \frac{2\beta_i - 1}{\beta_i + 1} a_e$$
$$= \left(1 - \frac{2(2\beta_i - 1)}{1 + \beta_i}\right) \Delta_N + \Delta_C + \frac{(2\beta_i - 1)}{1 + \beta_i} \Delta_C$$
$$= \frac{3 - 3\beta_i}{1 + \beta_i} \Delta_N + \frac{3\beta_i}{1 + \beta_i} \Delta_C = \frac{3}{1 + \beta_i} \left((1 - \beta_i)\,\Delta_N + \beta_i \Delta_C\right) > 0$$

□

Unfortunately, it follows directly from previous work [6] that the number of iterations to reach a Nash equilibrium can be exponential, and the problem of computing a Nash equilibrium is PLS-hard. For regular congestion games with matriod strategy spaces [1] Nash dynamics converge in polynomial time. It is an interesting open problem if a similar result holds here.

5 Stabilization Methods

This section treats a model in which an institution can convince selfish agents to act as altruists. For simplicity of presentation we first restrict to games with only pure altruists and egoists. A natural question for such an institution to consider is how many altruists are required to guarantee that there is a Nash equilibrium with a certain cost, e.g. a Nash equilibrium as cheap as a social optimum state. We term this number the *optimal stability threshold*. In a more pessimistic direction it is of interest to determine the minimum number of altruists needed to guarantee that the worst-case Nash equilibrium is optimal. We term this number the *optimal anarchy threshold*. Let us denote by n_1^+ and n_1^- the optimal stability and anarchy threshold, respectively. As a consequence from Theorem 4 we can compute both numbers for symmetric singleton congestion games in polynomial time. For each number of altruists we check if the best and/or worst Nash equilibrium is as cheap as the social optimum.

Corollary 10. *For symmetric singleton congestion games with only pure altruists and egoists there is a polynomial time algorithm to compute n_1^+ and n_1^-.*

Note that the optimal anarchy threshold is not well-defined, because the worst Nash equilibrium might always be suboptimal, even for a population of altruists only. In case of symmetric singleton games and convex delay functions, an easy exchange argument serves to show that in this case any local optimum is also a global optimum. However, for concave delay functions or asymmetric singleton games, a local optimum might still be globally suboptimal. Note that for symmetric games, our algorithm is able to detect the cases in which suboptimal local optima exist. In the asymmetric case, however, a similar approach fails, because of the NP-hardness of determining existence of a Nash equilibrium. Thus, in the following we concentrate on the optimal stability threshold.

In asymmetric games, it is also required to determine the identity of agents, so here we strive to find a set (denoted N_e^+) of minimum cardinality. For an optimal set of congestion values $n_E^* = (n_e^*)_{e \in E}$ we can determine $N_1^+(n_E^*)$ such that there is a Nash equilibrium of the game with congestion values n_e^* for all $e \in E$.

Theorem 11. *For singleton games with only pure altruists and egoists and a social optimal congestion vector n_E^* there is a polynomial time algorithm to compute $N_1^+(n_E^*)$.*

The theorem can be shown by constructing a complete bipartite graph. The nodes in one partition correspond to agents, in the other partition there are n_e^* nodes for each resource e. By appropriately assigning costs in $\{0, 1\}$ to the edges we can minimize the number of required altruists with a minimum cost perfect matching. The complete details are deferred to the full version.

This approach can be extended to an even more general natural scenario. Suppose each agent i has a *stability cost* c_{ie} for each strategy $e \in \mathcal{S}_i$. This cost yields the disutility for being forced to play a certain strategy given a congestion vector n_E. Here we redefine $N_1^*(n_E)$ to be the set agents of minimal stability cost. We can compute this set by a minimum weight perfect matching if we set the weights to c_{ie} for all edges connecting i to vertices of e. The stability cost allows for general preferences exceeding categories like altruists and egoists.

Corollary 12. *For singleton games and a congestion vector n_E there is a polynomial time algorithm to compute $N_1^+(n_E)$ with minimal stability cost.*

The underlying problem is a matching problem, which is solved optimally. Hence, it is possible to turn our approach into a truthful mechanism using VCG payments (see e.g. [19, chapter 9]). Our final mechanism (1) learns the stability costs from each agent, (2) determines the allocation, and (3) pays appropriate amounts to agents for truthful revelation of cost values and adaptation of allocated strategies. In addition, it can be verified that all computations needed require only polynomial time.

Corollary 13. *For singleton games and a congestion vector n_E there is a truthful VCG-mechanism to compute $N_1^+(n_E)$ in polynomial time.*

These general results are restricted to the case of singleton games. For more general games we show that it is NP-hard to decide if there is a Nash equilibrium as cheap as the social optimum. Our next theorem establishes this even for symmetric network congestion games with linear delays, in which an arbitrary Nash equilibrium and a social optimum state can be computed in polynomial time [6]. Furthermore, the result requires only a series-parallel network. Thus, even in this restricted case it is NP-hard to decide if the number n_1^+ of pure altruists required is 0 or 1, or equivalently if $N_1^+(n_E^*)$ is empty or not. This directly yields hardness of approximation within any finite factor.

Theorem 14. *For symmetric network congestion games with 3 agents, linear delay functions on series-parallel graphs and optimal congestions n_E^* it is* NP*-hard to decide if there is a Nash equilibrium with congestions n_E^*.*

We remark that the previous theorem contrasts the continuous non-atomic case, in which a minimal fraction of altruistic demand stabilizing an optimum solution can be computed in any symmetric network congestion game [13].

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