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Restricting the benefit flow from neighbors: Experiments on network formation

Siegfried K. Berninghaus*
and Marion Ott**
and Bodo Vogt***

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*Universität Karlsruhe , email: sbe@vwl3.wiwi.uni-karlsruhe.de

**Universitaet Karlsruhe, email: ott@wiwi.uni-karlsruhe.de

***Universität Magdeburg, email: bodo.vogt@ww.uni-magdeburg.de

Universität Mannheim
L 13,15
68131 Mannheim

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Siegfried K. Berninghaus[1] Marion Ott[2] Bodo Vogt[3]

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[1] *Corresponding author.* University of Karlsruhe, Institute WiOR, Zirkel 2, Rechenzentrum, D-76128 Karlsruhe (e-mail: berninghaus@wiwi.uni-karlsruhe.de).

[2]University of Karlsruhe, Institute WiOR, Zirkel 2, Rechenzentrum, D-76128 Karlsruhe (e-mail: ott@wiwi.uni-karlsruhe.de).

[3]IMWF, University of Magdeburg, Universitätsplatz 2, D-39106 Magdeburg (e-mail: bodo.vogt@ww.uni-magdeburg.de).

Abstract

In an experimental framework on network formation inspired by the two-way information flow model of Bala and Goyal (2000), we observe that many groups participating in the experiment reach the strict Nash network resp. come very close to this network. Compared to the results of previous network experiments this is new. Among other things, the role of inequity aversion in explaining our experimental results is discussed.

JEL classification: C72, C78, C92

Keywords: Network formation, Nash networks, network experiment

1 Introduction

Theoretical research on networks has attracted a lot of economists during the past 10 years. The approaches by Jackson and Wolinsky (1996), and by Bala and Goyal (2000) on network formation proved to be the most influential ones. The main idea of the network model in Bala and Goyal is similar to the model by Jackson and Wolinsky: Players obtain payoff from being connected with other players, but have to bear connection costs if they open links to their neighbors. Payoffs could be interpreted, for example, as generated by valuable information flows spreading through a network. In the literature, two different types of information flow are distinguished. In the *1-way flow model* information (and payoff) flows only to the player who opens a link. In the *2-way flow model* information (and payoff) flows both ways although only one player has to pay communication costs. In the model by Bala and Goyal, the decisions of agents in a network to sever or open links to other agents are strategic decisions in a non-cooperative normal form game called *network game*. Nash equilibrium in the network game seems to be a weak concept since the number of Nash equilibrium networks can become very large even in populations of moderate size. The *strict Nash* concept turns out to be an important refinement. Depending on the value of the communication costs in the 2-way flow model Bala and Goyal show that the empty network and the so-called *center sponsored star* are the only strict Nash networks which are also efficient.[1]

In contrast to theoretical work, until recently almost no experimental work on network formation has been published. Recent economic experiments are Plott and Callander (2002), Falk and Kosfeld (2003), and Deck and Johnson (2004). It was the main purpose of their investigations to show whether subjects reach Nash equilibrium resp. strict Nash equilibrium networks. In the 2-way information flow experiment by Falk and Kosfeld it is one of their most important findings that in a 2-way flow network game subjects never form strict Nash networks (within 15 rounds). Social motives like *inequity aversion* are used to explain the results.

Since we want to exclude a strong influence of such social motives on network formation we propose a different experimental design in which strict Nash networks evolve significantly more often than in previous studies. In our framework, an agent does not have access to the payoff of all agents which are only indirectly linked to him. An important consequence of this assumption is that the *periphery sponsored star*[2] becomes a strict Nash network (instead of a center sponsored star). Center players in a periphery sponsored star seem to be found easier than center players in a center sponsored star. Actually, we find that 30% of all participating groups in our experiment reach strict Nash networks or at least remain very close to it. We do not know of any other network experiment conducted so far in which strict Nash networks have been reached so often.

[1] The center sponsored star is characterized by one player (the center player) opening links to all other players, while no other player opens a link.

[2] The periphery sponsored star is characterized by all players except for the center player opening direct links to the center player while the center player himself does not open any link.

2 The network game

The network game is characterized by the set of players $I = \{1, \ldots, n\}$, the strategy sets G_i, and payoff functions $\Pi_i(\cdot)$. An individual strategy in the network game of player i is a vector of ones and zeros $g_i \in G_i := \{0,1\}^n$, where player i establishes a link to player j if $g_{ij} = 1$, otherwise $g_{ij} = 0$. By convention a player cannot link with himself, that is $g_{ii} := 0$ for all i. Note, that a bilateral connection between two players in our model is supposed to be already established if at least *one* player wants to open it, i.e. if $g_{ij} + g_{ji} \geq 1$ holds. Each strategy configuration $g = (g_1, \ldots, g_n)$ generates a directed graph denoted by $\mathcal{G}_g$, where the vertices represent players and a directed edge between i and j, i.e. $g_{ij} = 1$, indicates that i opens a link with j.

In our model we distinguish three types of neighbors, given a network $\mathcal{G}_g$.
Actively reached neighbors are all players to whom i opens a link, that is,

$$N_i^a(g_i) := \{j \in I \mid g_{ij} = 1\}.$$

Passive neighbors are all players who open a link with i, that is,

$$N_i^p(\mathcal{G}_g) := \{j \in I \mid g_{ji} = 1\}.$$

Indirect neighbors are all actively reached or passive neighbors of all actively reached neighbors of i, i.e.,

$$N_i^{ind}(\mathcal{G}_g) := \{k \in I \mid \exists j \neq i \neq k : \; g_{ij} = 1 \text{ and } \max\{g_{jk}, g_{kj}\} = 1\}.$$

Thus, the set of *all neighbors* of player i is given by

$$N_i(\mathcal{G}_g) := N_i^a(g_i) \cup N_i^p(\mathcal{G}_g) \cup N_i^{ind}(\mathcal{G}_g).$$

Let $n_i(\mathcal{G}_g)$ denote the number of elements in $N_i(\mathcal{G}_g)$ and $n_i^a(g_i)$ the number of elements in $N_i^a(g_i)$.

Costs for opening a link are supposed to be the same for each player and denoted by c (> 0). The payoff player i can extract from being linked (either actively, passively or indirectly) to player j is the same for all players and supposed to be equal to a (> 0). Given strategy configuration $g = (g_1, \ldots, g_n)$, player i's payoff is given by

$$\Pi_i(g) := a \; n_i(\mathcal{G}_g) - c \; n_i^a(g_i). \tag{1}$$

For network games $\Gamma = \{G_1, \ldots, G_n; \; \Pi_1(\cdot), \ldots, \Pi_n(\cdot)\}$ a *Nash network* is defined to be a vector $g^* = (g_1^*, \ldots, g_n^*)$ such that no player has an incentive neither to open nor to sever links nor to simultaneously open and sever links generated by g^* unilaterally.

In contrast to Bala and Goyal's original model, we obtain different theoretical results.[3] The drawings in Figure 1 illustrate the difference of a center sponsored star and a periphery sponsored star in a population of six. No non-strict Nash network of Γ was observed in the experiment. We will restrict ourselves to derive sufficient conditions to characterize a strict Nash network. Graphs of all classes of Nash networks can be found in Appendix A.

[3]Most important, a center sponsored star is not even a Nash network (for $c < a$) since any periphery player can strictly improve his payoff by opening a link to any other player.

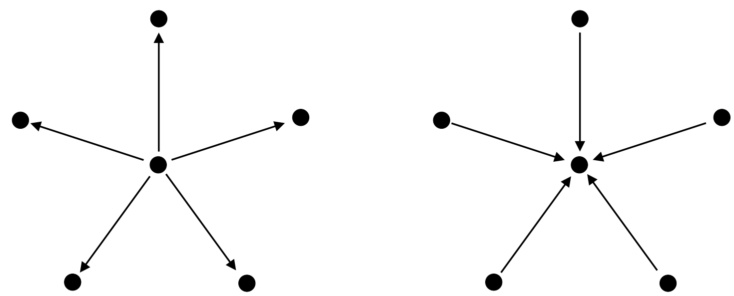

Figure 1: a) center sponsored star b) periphery sponsored star

Proposition 1 *If $c < (n-1)a$, then a periphery sponsored star is a strict Nash network.*[4]

3 Experimental design

Our computerized experiment was performed partly in the experimental laboratory at the University of Karlsruhe and partly at the experimental laboratory at the Sonderforschungsbereich 504 (University of Mannheim). Subjects were selected from a pool of various students enrolled at different departments. Our experiment was organized in 4 sessions where 18 subjects participated in each of the sessions one and two respectively while 12 subjects participated in each of the sessions three and four. The experiment was programmed and conducted with the software *z-Tree* created by Urs Fischbacher (Fischbacher, 1999).

Subjects in each session were divided into groups of 6 players who played the network game Γ for 15 rounds.[5] At the beginning of each round, each player with a mouse click had to choose no more than 5 links to other players. Activated links of a player were marked by red arrows in a given diagram on the screen. After each player in the group had made his decision the resulting network was shown on the screen. In the following round, a new drawing appeared on the screen in which each player could again activate links. Note that a player's links of the previous round were dropped when a new round started. However, the graph of the previous round was additionally shown on the screen so that players could base their decisions on a 1-round history. All groups started with the same complete network[6] (in a fictive round 0).

Payoffs per connection were set equal to 3 ECU (=experimental currency units). Costs per link were 2 ECU. Net payoffs for each subject were accumulated over 15 rounds and payed out in cash shortly after the experiment had been finished (conversion rate: 12 ECU = 1 €). The payoff of each player before decision making started was fixed (at 5 ECU) since all groups had to start with the same (complete) network. Although the number of rounds for each group was fixed in advance total time spent in the laboratory

[4]A periphery player in a periphery sponsored star obtains net payoff equal to $a(n-1) - c$ which is strictly reduced by changing links unilaterally. The center player receives net payoff equal to $a(n-1)$ which is the maximal possible payoff and is strictly reduced if the center player opens a link.

[5]The detailed experimental instructions can be found in Appendix B.

[6]Where all players are directly connected with each other.

was not fixed since the next round started only when all group members had submitted their linking decision to the experimenter. The maximum payoff (resp. minimum) payoff earned was equal to 16.42 € (resp. 10.08 €). The average payoff was 13.71 €.

4 Experimental results

4.1 Describing the results

How many groups reached a strict Nash network[7], that is, a periphery sponsored star or stayed at least close to it after some rounds had elapsed?

Our definition of *being close* with respect to networks is based on the observation that even in groups which did not reach a strict Nash network subjects seemed to try to find a group member which could be designated as center player with whom they wanted to be connected. Let us denote by $Indeg(x_i)$ the in-degree of vertex x_i that represents player i in the graph $\mathcal{G}$, i.e. $Indeg(x_i)$ is equal to the number of player is passive links. We focus on networks in which the maximum in-degree is larger than or equal to 3, since such groups seem to be "on the way" to a periphery sponsored star. In such networks we define our distance measure $d(g)$ of a strategy configuration g from a periphery sponsored star as follows. Let index i^* be defined by $Indeg(x_{i^*}) \geq Indeg(x_j)$ then we define

$$d(g) := \begin{cases} 5 & if \quad \max_{x_i}\{Indeg(x_i)\} < 3 \\ \mid (Indeg(x_{i^*}) - \max_{x_j}\{Indeg(x_j)\}) - 5 \mid & if \quad \max_{x_i}\{Indeg(x_i)\} \geq 3 \end{cases}$$

This distance concept compares players with maximum in-degree (=possible central player) and second highest in-degree. If the maximum in-degree is smaller than 3 then $d(g)$ is equal to 5. If $Indeg(x_{i^*}) \geq 3$ and the maximum in-degree is not unique, $d(g)$ is equal to 5 either. Intuitively, when the difference between the maximum and the second highest in-degree is small we are still quite distant from a periphery sponsored star shaped network. When subtracting 5 from this difference the distance measure $d(g)$ is rather large. On the other hand, we have $d(g) = 0$ only for a periphery sponsored star. The evolution of the distance measure for all groups over 15 rounds is shown in Table 1. From Table 1 we conclude:

Fact 1 *a) Three groups (out of ten) reached a periphery sponsored star (groups 5, 6, 10).*
b) Two other groups (groups 4, 8) came very close to a periphery sponsored star.

Summarizing, about 50% of all groups reached the strict Nash network which distinguishes our results from those obtained by Falk and Kosfeld in the original Bala/Goyal design where players have access to all neighbors of a neighbor who can be reached via a path. Let us call the groups enumerated in Fact 1 "successful". The development of the networks of the successful groups is graphically displayed in Appendix C.

[7]Note that no group reached a non-strict Nash network during the course of the experiment.

	groups									
Round	1	2	3	4	5	6	7	8	9	10
1	4	5	4	3	5	4	5	4	4	4
2	4	4	4	2	4	5	4	5	4	5
3	5	5	5	5	4	4	4	2	5	5
4	5	5	4	5	2	2	5	3	3	3
5	5	3	5	5	2	1	5	4	5	3
6	4	4	3	5	2	3	4	4	5	2
7	5	4	5	4	1	1	3	2	5	1
8	4	4	4	5	1	1	5	3	3	1
9	5	5	4	5	0	0	4	2	4	1
10	4	3	4	4	0	0	5	1	4	0
11	5	3	4	4	0	0	4	1	4	0
12	3	4	4	4	0	2	5	2	5	1
13	5	3	5	3	0	1	5	1	4	0
14	4	5	5	1	0	0	5	2	3	0
15	5	3	4	1	0	0	4	1	2	0

Table 1: Evolution of distance measure $d(g_t)$ for $t = 1, \ldots, 15$

4.2 Discussing the results

We elaborate on three aspects which may highlight the driving forces of our results. Falk and Kosfeld (2003) argue that in their experiment subjects probably did not find the strict Nash network (in their framework: the center sponsored star) since their design is too complex and since *inequity aversion* prevents them from reaching a strict Nash equilibrium.

α) The complexity argument: Complexity in this experiment arises from the fact that the strict Nash network (the star) is not *symmetric*. In our context, one player had to drop all links while the remaining players establish one link to him. In the Falk and Kosfeld setting, one player has to establish links to all other players who have to be passive (form no links).

We assume that it is easier to understand that forming links may increase payoff when $c < a$ than to understand that being passive might be "optimal". In our setting, in the strict Nash equilibrium only the center player has to understand that building no links is optimal for him. In the Falk and Kosfeld setting, $(n-1)$ periphery players have to be passive to reach the center sponsored star. Plott and Callander (2002) explain the realization of stable networks in experiments by successful coordination of beliefs: "... at certain critical points in network dynamics the coordination, bargaining and free rider aspects of individual decision making become aligned and stability is achieved. At these points it appears that all decision makers become aware of which network is best for them, and are aware that other agents are aware of this, and so on ad infinitum. Coordination of beliefs seems to be easier in our framework.

β) The inequity aversion argument: Falk and Kosfeld (2003) argue that inequity aversion may be another obstacle to subjects not reaching a center sponsored star. Concerning their experiment, there is indeed a significant inequity of payoffs between a center player and a periphery player which may prevent players from approaching center sponsored stars. However, in our design the difference is not that big. A center player in a periphery sponsored star earns 15 ECU while a periphery player earns 13 ECU. This is due to the fact that we "cut off" paths between two players in the network that include more than 2 edges. In fact, our results support the conjecture by Falk and Kosfeld and show that the *inequity aversion hypothesis* in network formation cannot be refuted.

γ) The activity argument: Our results show an additional relevant determinant of network formation. Considering the behavior of subjects in the successful groups we observe that there exist some group members who show a significantly high degree of *inertia*. Most of these players, from some round on, hold only one link and do not change this link until the end of the experiment (see Table 2). They seem to have realized that the group would benefit most from building a periphery sponsored star (see also the argument by Plott and Callander cited in α)).

In contrast, in most of the unsuccessful groups some of the players who build the same links from some round on until the end build two links.

number of players	group 10	5	6	4	8	1	2	3	7	9
1	4 [1]	3 [1]	2 [1]	5 [2]	1 [1]	6 [2]	13 [2]	1 [2]	9 [2]	11 [1]
2	4 [1]	4 [1]	5 [1]	8 [1]	7 [1]	10 [1]	13 [1]	9 [2]	13 [1]	14 [1]
3	6 [1]	4 [1]	13 [1]	10 [1]	7 [1]	12 [2]	–	12 [2]	–	14 [1]
4	7 [1]	6 [0]	13 [1]	11 [1]	9 [1]	–	–	14 [2]	–	14 [1]
5	10 [0]	8 [1]	14 [0]	13 [1]	–	–	–	–	–	–
6	13 [1]	9 [1]	14 [1]	14 [1]	–	–	–	–	–	–

Table 2: Number of group members with fixed links: First round of inertia (if < 15) and number of links (in squared brackets)

Let us define the *degree of inertia* of a group as the average number of rounds (over all group members) in which a group member did not change his links. In Table 3 we arrange the groups participating in our experiment according to the degree of inertia. Table 3 shows that the five best groups ranked according to the degree of inertia are

degree of inertia	11.50	11.33	9.67	9.33	8.50	7.00	4.33	4.17	4.00	3.17
ranked groups	10	5	6	4	8	1	2	3	7	9

Table 3: Inertia and group success

exactly the same groups which reached a periphery sponsored star resp. came close to it.

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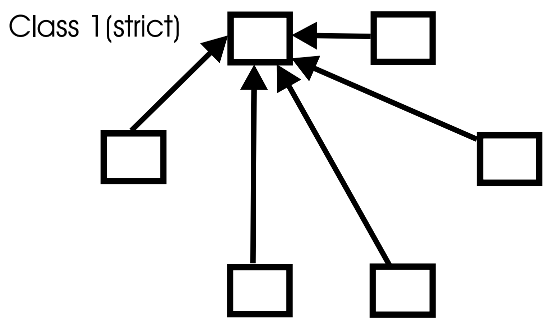
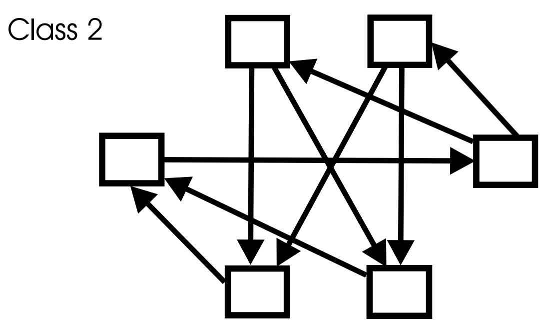
A Classes of Nash networks for our experimental design

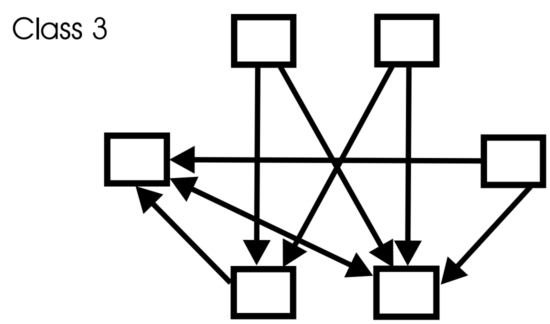
In simulations we found 3666 Nash networks, where 6 are strict Nash. After determining the equivalence classes[8] we obtained 11 classes of different size. The size gives the number of networks in a class, for example six periphery sponsored stars, as every player can be the center player. We present these classes of Nash networks below. Each class is represented by a non-labeled directed graph. Class 1 consists of all strict Nash networks, i.e., of all periphery sponsored stars. The remaining classes 2–9 are non-strict Nash networks.



Class 1 of strict Nash equilibria (size 6)

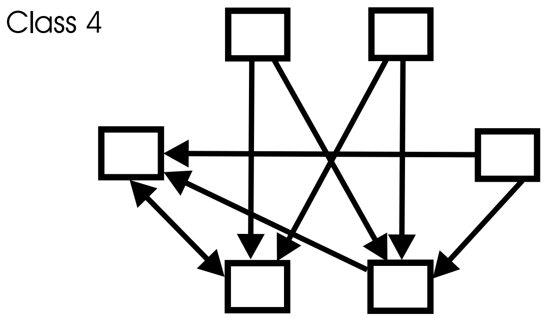


Class 2 of Nash equilibria (size 180)

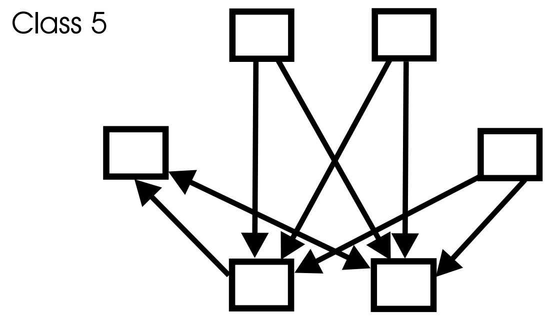


Class 3 of Nash equilibria (size 360)

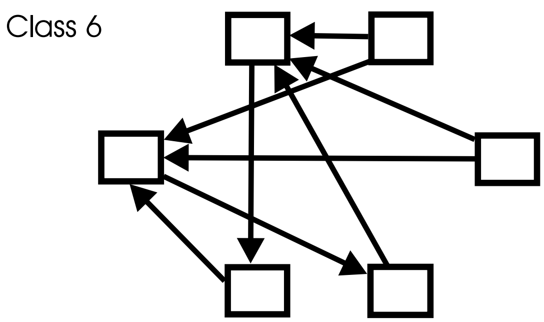
[8] In graph theory the networks that belong to the same class are called isomorphic graphs.



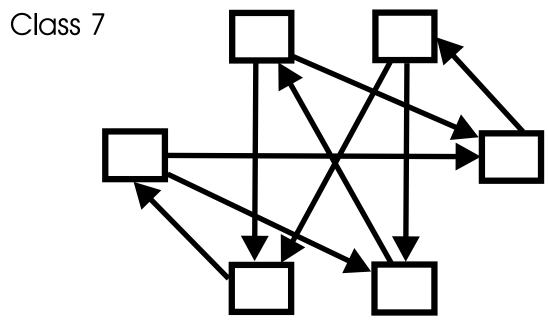
Class 4 of Nash equilibria (size 360)



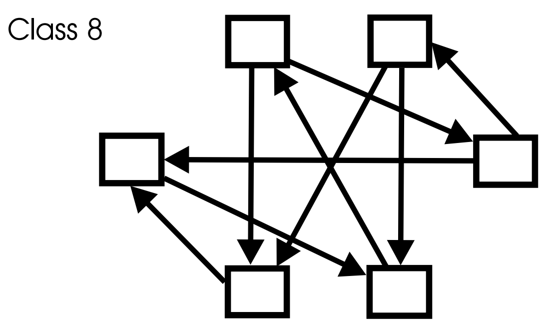
Class 5 of Nash equilibria (size 120)



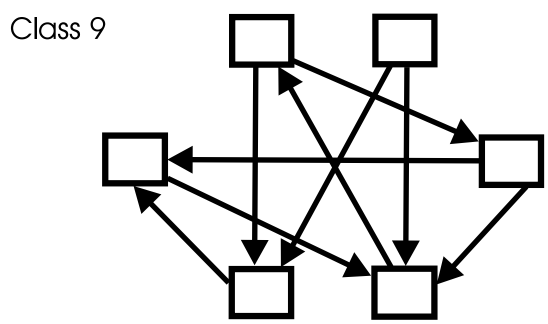
Class 6 of Nash equilibria (size 180)



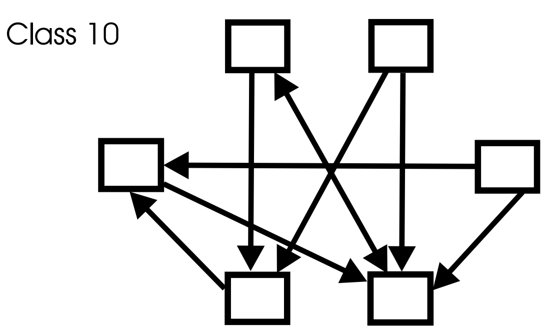
Class 7 of Nash equilibria (size 120)



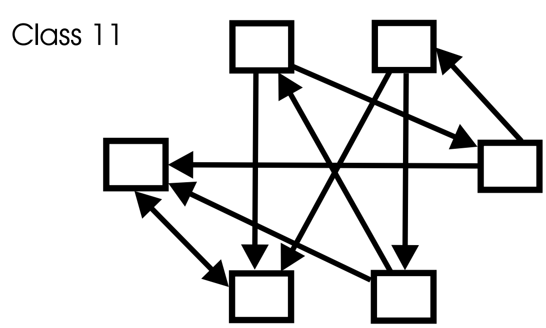
Class 8 of Nash equilibria (size 720)



Class 9 of Nash equilibria (size 720)



Class 10 of Nash equilibria (size 720)



Class 11 of Nash equilibria (size 180)

B Experimental instructions

Instructions

You are participating in an experiment on interactive decision making. In this experiment, you can earn cash. How much you earn, depends on your own decisions and the decisions of the other participants. In the experiment, payoffs earned are measured in so-called **currency units** [CU]. The sum of currency units you earn in total will be transformed into Euro at the end of the experiment and paid out in cash. Each participant makes his decisions separate from the remaining participants sitting at his computer-terminal. Communication between participants is not allowed.

At the beginning of the experiment, you will be randomly matched with five other participants to form a **group of six**. The participants of a group are not necessarily sitting side by side. The composition of a group persists during the course of the experiment. There is no interaction with other groups. The six members of your group will be randomly assigned the labels *T1*, *T2*, *T3*, *T4*, *T5*, and *T6*. You will find your own label within your group on your screen at the beginning of the experiment. In the following, the term "participant" will be used only to denote participants of your group. Any other participant in your group obtains exactly the same instructions as you do.

The experiment runs for **15 rounds**. Each round has the same structure and consists of two stages.

In each round's **first stage**, you can open connections to the other participants of your group. In the **second stage**, you will see all connections which have been built by participants in your group, and you obtain a profit, the size of which depends on the connections proposed by all group members.

Connections

Types of connection: There are three ways to be connected to other participants in your group.

You can decide to open connections to other participants by yourself. These connections will be called your **active connections** in this round. Your active connections will be displayed as arrows pointing from you to other participants.

In each round, you can build active connections to as many participants as you want. However, to each participant you can only open one active connection per round.
The participants to whom you have opened an active connection will be called your **actively reached participants**. Example: In the network on page 3 in the lower left corner of Figure 2, only *T2* is actively reached by *T1*.

In addition to your actively reached connections, your so-called **passive connections** and your **indirect connections** are also relevant for you. A passive connection for you is a connection, that another participant opened to you. That is, it is a participant's active connection to you. Example: In Figure 2 (lower left edge) *T1* has a passive connection with *T6*.

The **passive and active connections of your actively reached participants** are called your **indirect connections**. In other words, these are the passive and active connections of those participants, to whom you have an active connection. Through your passive connections you do not have access to indirect connections.

A participant cannot open connections with himself.

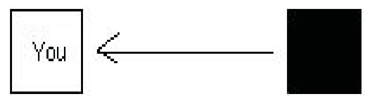
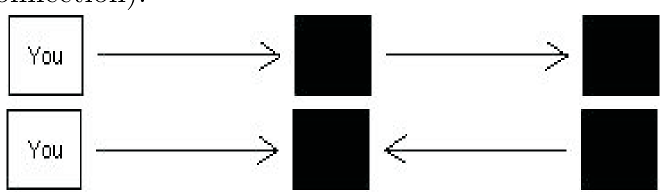
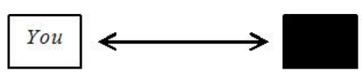
Type of connection	Meaning
1. active	Your connection to another participant. Graphical illustration: 
2. passive	Other participant's connection to you. Graphical illustration: 
3. indirect	Active and passive connections of a participant, who is actively reached by you. Graphical illustration (two possibilities of indirect connection): 

Table 1: Types of connection

If you have an active and a passive connection to a participant at the same time, it will be displayed as a double arrow.



The following Figure 1 illustrates the meaning of the denotations "active," "passive" and "indirect" connection from *T1*'s **point of view**. This figure only helps the illustration. In the experiment, the arrows will neither be labeled nor broken (in Figure 2 in the lower left corner you can see, what the network of Figure 1 will look like in the experiment).

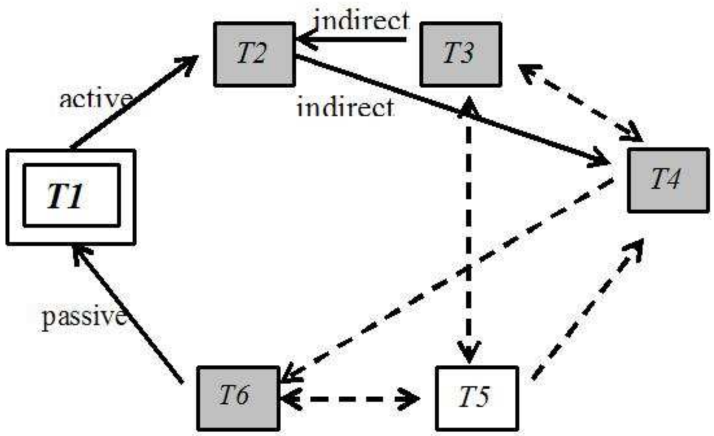


Figure 1: Types of connection from *T1*'s point of view

The arrowheads in Figure 1 point away from the participant, who has opened the connection. The dashed arrows have no consequences for *T1*'s profit. *T1* is connected with the participants *T2*, *T3*, *T4* and *T6* marked in grey (in the experiment: black marking, see lower left corner of Figure 2). *T2* is actively reached by *T1*, since *T1* has an active connection to *T2*. *T1* is indirectly connected to *T3* and *T4*, because *T2*, who is actively reached by him, is passively resp. actively connected with them. *T1* is passively connected to *T6*. *T1* is not connected with *T5*.

Establishing connections: In the first stage of a round a so-called line network (Figure 2, upper part) is shown to you. Its edges indicate all possible connections between the members of the group.

You can mark active connections to other participants by clicking on one ore more lines, heading from you (box marked in red) to another participant. You can only choose some of the five edges pointing away from you. If you click on one of these edges, it will become bold and will be marked in red color. It will point to the participant you selected. In the example in Figure 2 (upper part) *T1* marked two connections to *T3* and *T5* respectively. In the lower right corner of the screen, the display of the associated active connection switches from "no" to "yes" when marking a line. You can make your marks disappear by clicking on the line a second time (the red arrow switches back to a black line and the display in the lower right corner switches back to "no"). If you click on the same line again it will again be marked red and so on. You can submit your final decision by clicking on the OK-button.

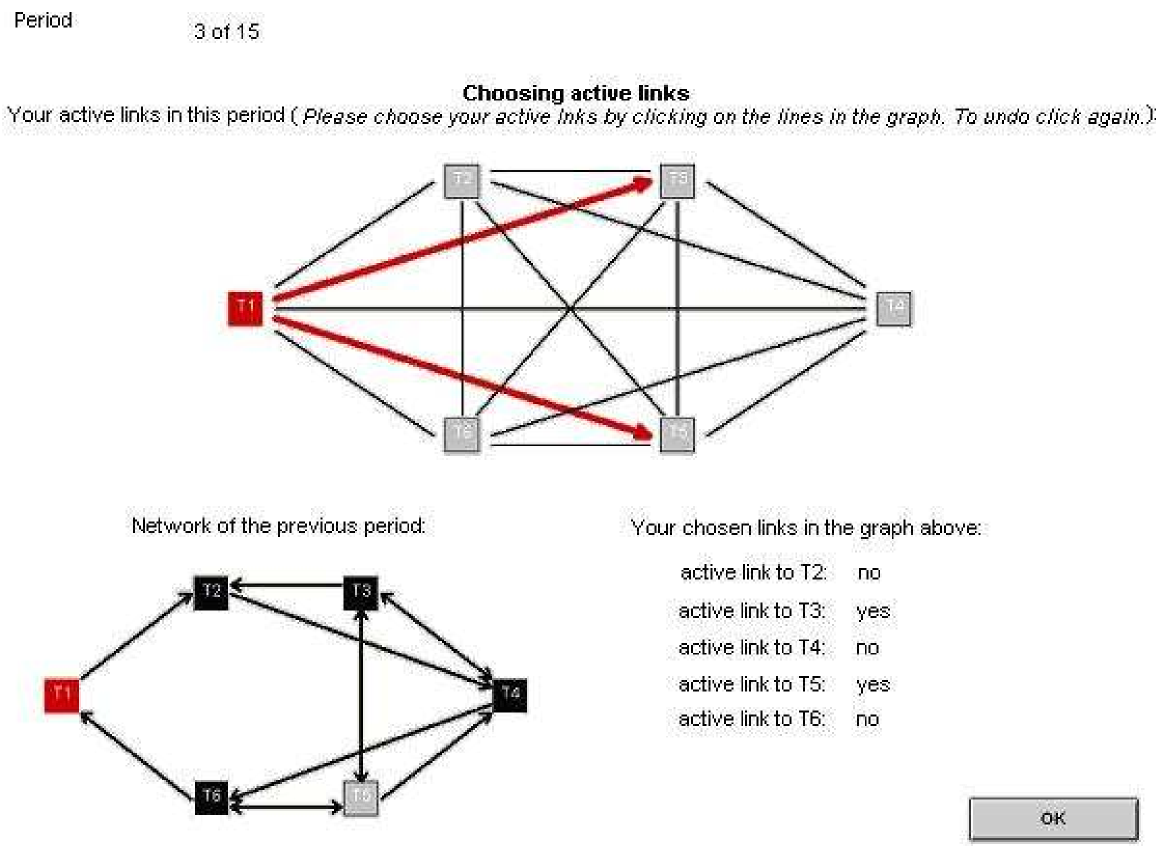


Figure 2: Screen plot of *T1* - first stage: Choice of active connections and display of the last round's network

When a new round starts, the line network in Figure 2 (upper part) only contains all possible links from a player to the remaining group members. None of the links is displayed as a red arrow yet. Your active connections of the previous round will **not be carried over**. In each round, you can open zero to five links to arbitrary participants in your group.

In the second stage of each round, the network built in the first stage of the round will be shown to you. You see all connections, that you and the other participants have chosen in the first stage of the round, displayed as arrows. All participants to whom you have an active, passive or indirect connection, following the rules given above, are **marked in black** (similar to the network in the lower left corner of Figure 2).

Network of the previous round: In the lower left corner of Figure 2, you see the network of the previous round. It is exactly the network, that has been shown to you in the second stage of the previous round.

Costs and earnings

Now you are informed about all three types of connection. In this section, we explain, how your earnings are determined.

<u>**Costs**</u>: Each **active connection** that you have chosen in the first stage of a round generates **costs equal to 2 CU**. Your passive and indirect connections do not incur connection costs. That is, each connection is paid by the player who opened it. In the case of double arrows ($\longleftrightarrow$), this means that both players have to pay for the connections they opened.

<u>**Earnings**</u>: Your earnings are determined by the number of participants you are connected with.
For each participant you are connected with (either actively, or passively, or indirectly), you obtain an **amount of 3 CU**. The participants you are connected with (either actively, or passively, or indirectly) in the second stage of a round as well as in the display of the network of the previous round are **marked in black** (as mentioned before).
Multiple connections with a participant (e.g. simultaneously active and passive connections to the same participant) do not generate multiple earnings. Example: *T5* in Figure 1 earns only 3 CU through his connection with *T3*, although he has an active, a passive, and an indirect connection with *T3*.
Your **earnings of one round** are calculated as follows: Count the number of participants you are connected with (maximum 5) and multiply it by 3 CU. Your earnings are then between 0 CU and $5 \cdot 3 = 15$ CU.

<u>**Profit**</u>: Your **profit** is the sum of your earnings in a round minus your costs from active connections in this round.

Profit = (Sum of earnings) - (Costs from active connections)

Your **accumulated profits** in a round equal the sum of all your profits up to the current round.

First Round

Other than in the remaining rounds, the **first round** starts by displaying a given complete network (of the fictive round 0) where each participant is actively connected with all other participants. For each of your active connections you pay the costs of 2 CU and you receive the earnings for the connections. All participants obtain the same net profit which is equal to $15 - 10 = 5$ CU. This will be credited to your account in the first round.

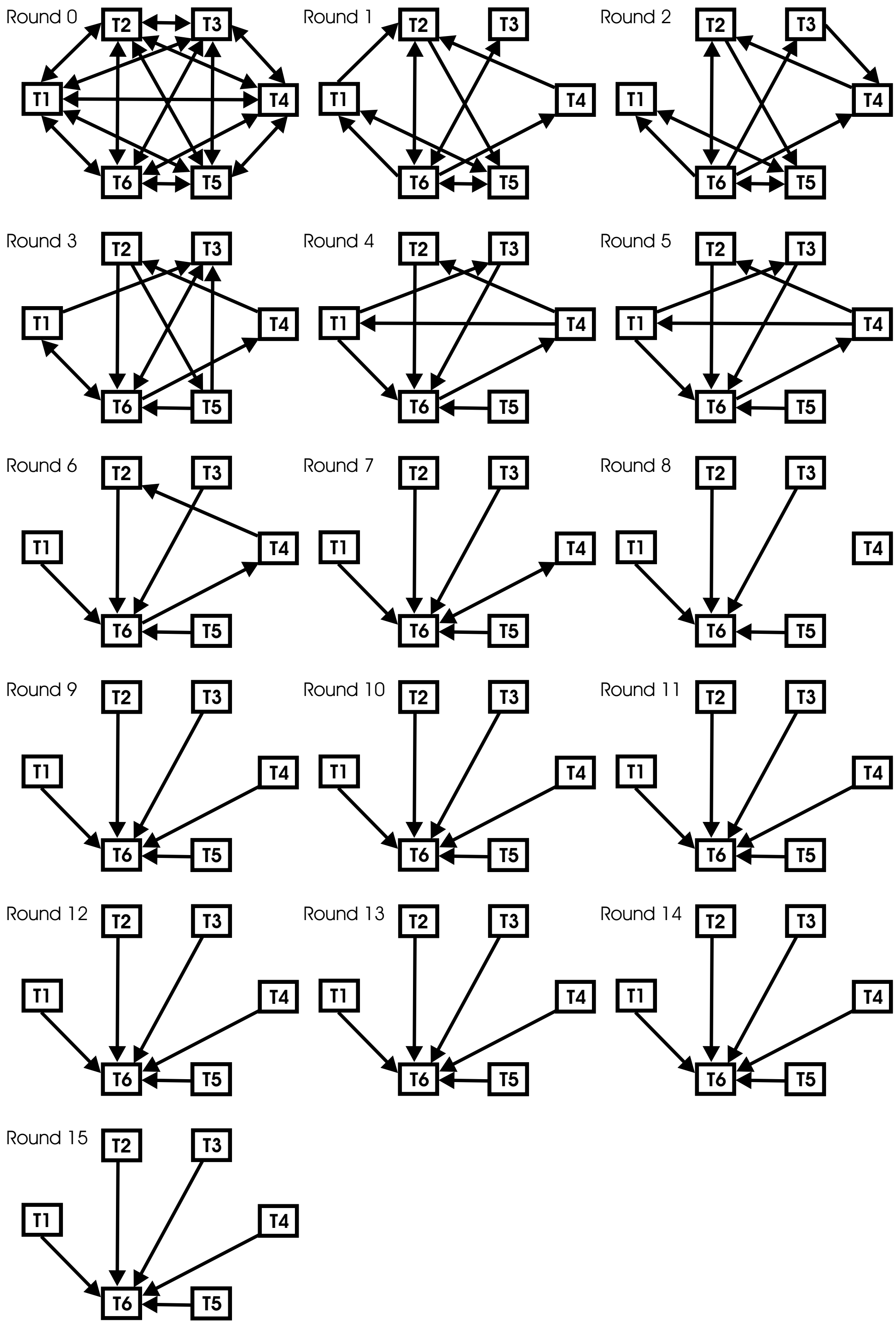
Payment

After the end of the 15 rounds, your accumulated profits will be calculated in Euro. The conversion rate is **12 CU to one Euro**.
When the experiment is finished, the amount of Euro you have earned will be paid out in cash. The payment will be made individually and anonymous.

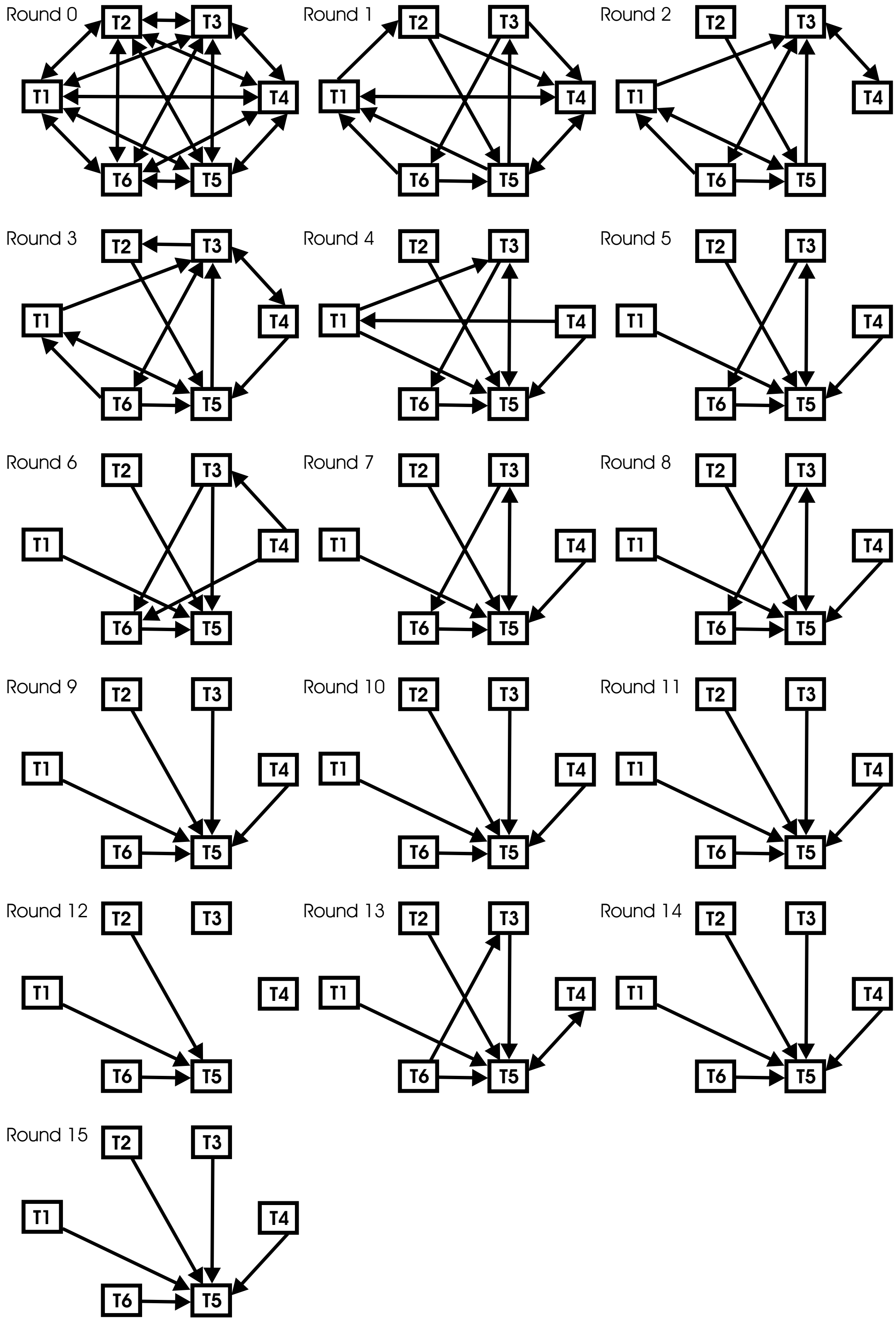
Hint: When choosing your active connections there is a little time delay until the arrow appears marked by bold red colour. Clicking one time is sufficient, a double-click is not necessary. Do not click again on the line too fast, otherwise, the arrow might disappear again. Please, wait before you click on the "OK-button", to guarantee that all planned active connections are transmitted. Check if all chosen active connections in the display at the bottom right have switched from "no" to "yes".

Before the experiment starts, you will be asked some questions about the rules of this game. If there is anything you do not understand, let us know. Your questions will be answered directly at your seat.

C Development of the networks of successful groups



Group 5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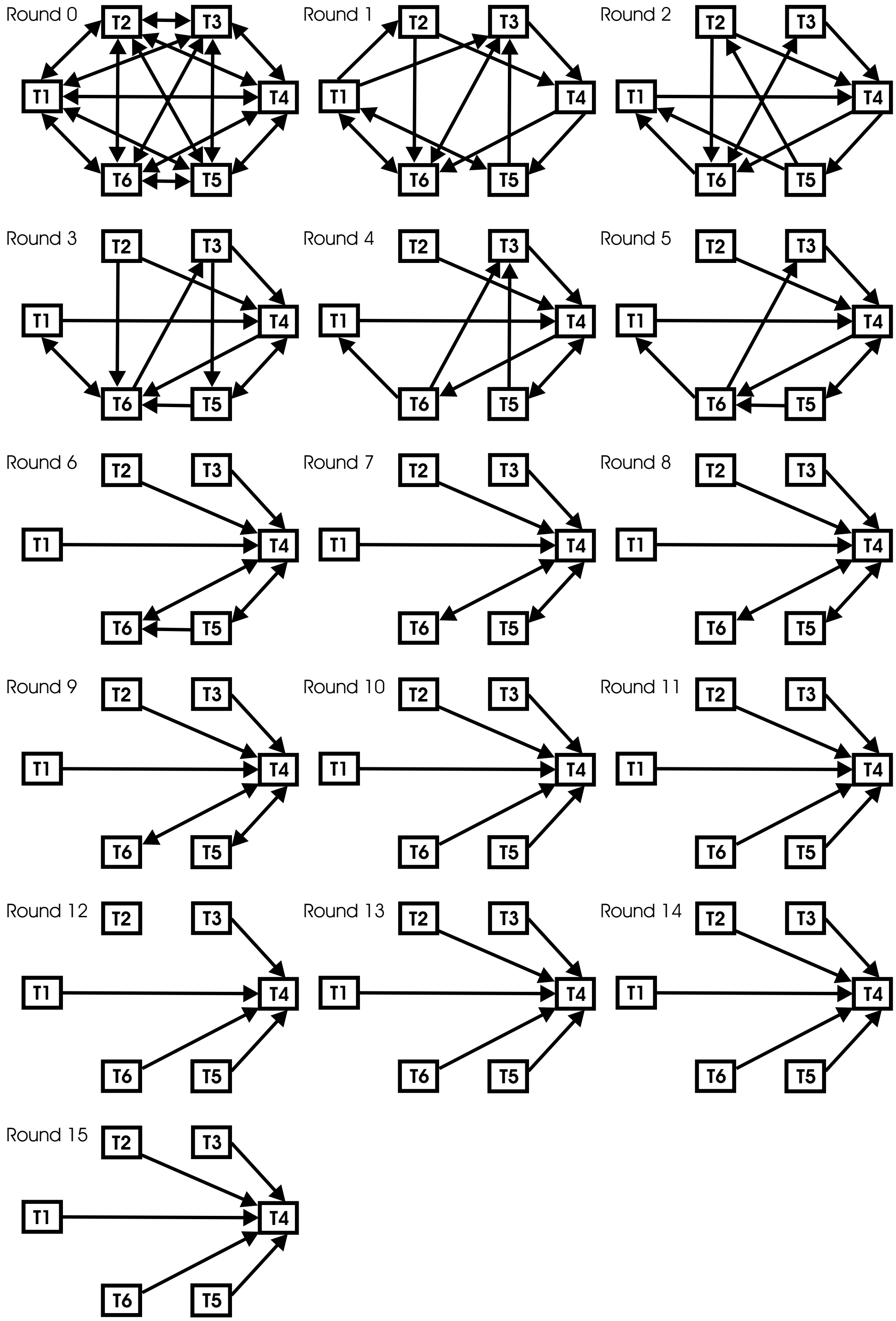
Round 14
Round 15

Group 6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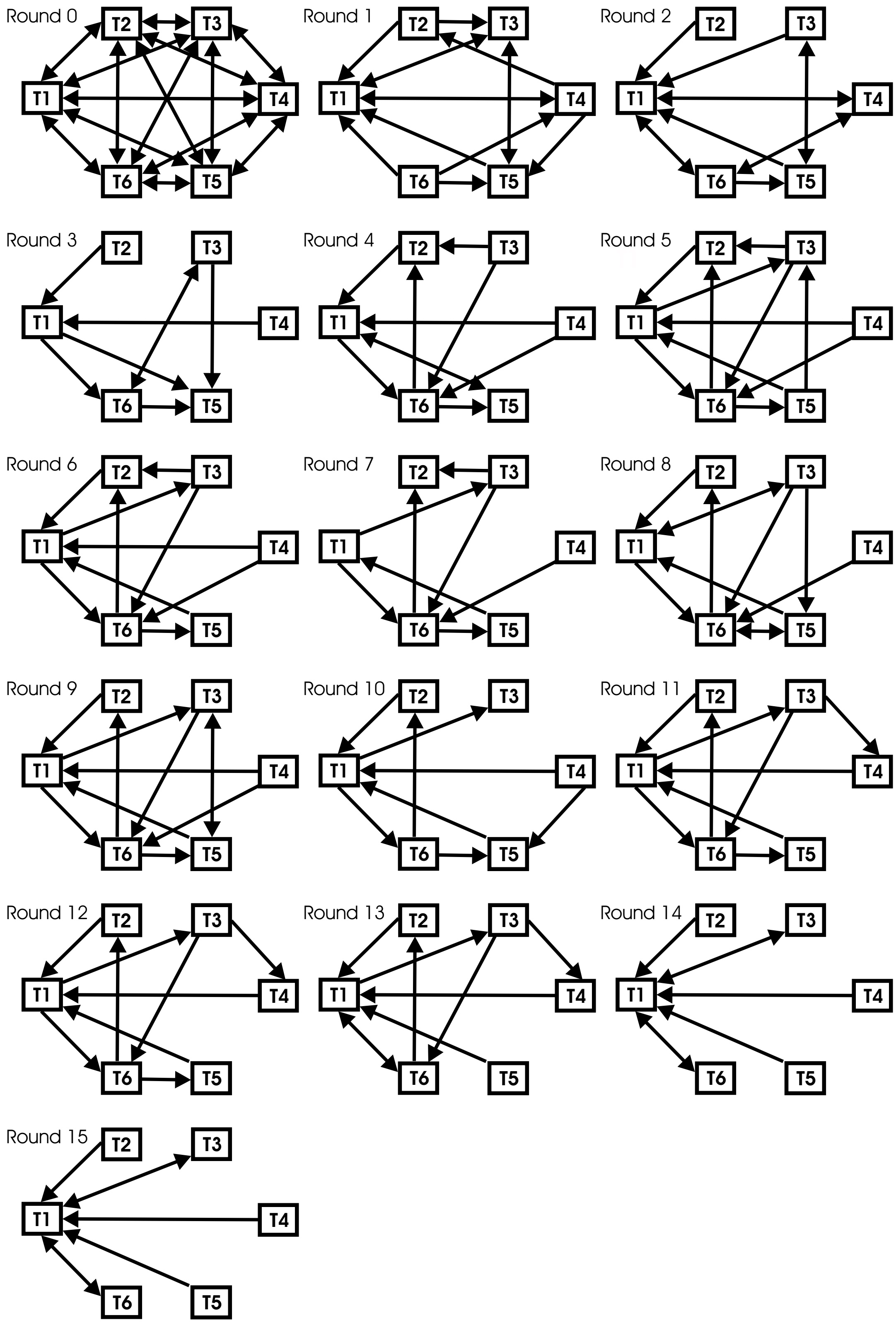
Group 10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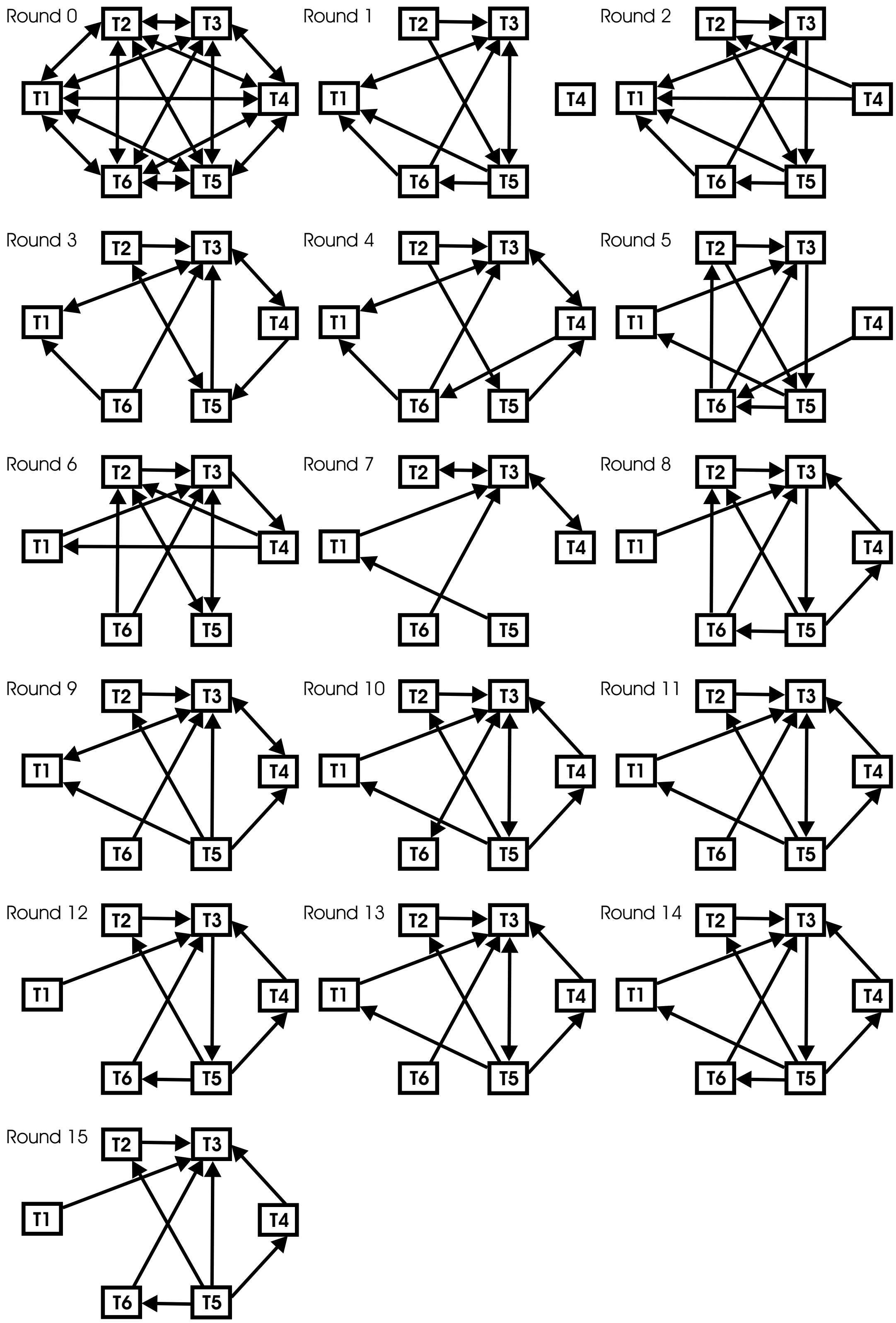
Group 4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Round 15
T1
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T3
T4
T5
T6

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