Network Formation and Disruption - An Experiment
Are efficient networks too complex?

Sonja Brangewitz, Behnud Mir Djawadi, Angelika Endres and Britta Hoyer

Paderborn University, Faculty of Business Administration and Economics
Warburger Str. 100, 33098 Paderborn, Germany

[sbrangew | bdjawadi | aendres | bhoyer] @mail.upb.de

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Abstract

We experimentally study the emergence of networks under a known external threat. To be more specific, we deal with the question if subjects in the role of a strategic Designer are able to form safe and efficient networks while facing a strategic Adversary who is going to attack their networks. This investigation relates theoretical predictions by Dziubiński and Goyal (2013) to actual observed behaviour. Varying the costs for protecting nodes, we designed and tested two treatments with different predictions for the equilibrium network. Furthermore, the influence of the subjects' farsightedness on their decision-making process was elicited and analysed. We find that while subjects are able to build safe networks in both treatments, equilibrium networks are only built in one of the two treatments. In the other treatment, predominantly safe networks are built but they are not efficient. Additionally, we find that farsightedness –as measured in our experiment– has no influence on whether subjects are able to build safe or efficient networks.

Keywords: Networks Experiment Network Design Network Defence Network Disruption

1 Introduction

Networks are ubiquitous in all fields of society and economy: Companies depend crucially on transportation and distribution networks whereas social relations and companies depend on communication or information networks. Being a member of such an interconnected system often proves to be beneficial. For example, companies profit from networks in the form of supply chains due to the possibility to create and maintain competitive advantages (Pelliccia, 2015). Among others a network's benefit depends on the network structure and the associated costs. The more players in the network, the more each player can potentially benefit from the connections. However, before benefiting from it, one first has to invest in building and maintaining links within the network, which demands time and effort (Morbitzer et al, 2012). Next to its structure, the benefit of a network is also influenced by its reliability. Thus, if the network is easily destroyable, it might not be worth to invest in being part of the network. To guarantee the reliability of the network, the network itself must withstand attacks on its components. For example, attacks can happen as faults of the structure of the network itself, disturbances via individuals within the network, or external strategic or random attacks. Random attacks are often found in epidemiology (Cerdeiro et al, 2015) or in climatology in the form of natural disasters such as floods and earthquakes. Strategic attacks can target information, communication or financial networks (Haller, 2016), for example, and can be conducted in the form of intelligent human attacks such as terrorist attempts (Arce et al, 2012).

Attacks can be targeted at the nodes of the network or at its links and, thus, can have severe consequences on the functioning of the network: Especially in complex network structures there exist inevitably specific nodes or links which are essential for the network to work. Attacks on these targets are often sufficient to disconnect the whole network (Kovenock and Roberson, 2015). An example for critical nodes in networks are servers which are threatened by viruses and cyber-attacks (Goyal et al, 2016). Critical link targets are trade-paths between countries (Pelliccia, 2015), the wires of power grids or the pipes of oil systems, for example. In all cases, an attack might affect the connectivity of the whole network.

In economics, network disruption has so far mainly been analysed in the context of its effect on network formation. Thus, the main question is how the threat of an attack will influence the initial formation of the network. This work deals with this question by building on the theoretical work on strategic network formation, which, in economics, has been founded by the seminal papers of Bala and Goyal (2000) and Jackson and Wolinsky (1996). The streams of models based on these basic network formation models analyse the influence of the threat of disruption on network formation and can be split into research about attacks on the links of the network (see, e.g., Bravard et al 2017, Hoyer and De Jaegher 2016 or Haller 2016) and research about attacks on the nodes of the network (see, e.g., Dziubiński and Goyal 2013, Dziubiński and Goyal 2017, Goyal and Vigier 2014, Cerdeiro et al 2015, Pelliccia 2015, or Kovenock and Roberson 2015). Additionally, Hoyer and De Jaegher (2012) analyse both link and node disruption in a decentralized model of network formation, where the nodes themselves decide on links, and compare the results.

While this theoretical literature on network formation and the influence of disruption on the formation process is growing, there are only relatively few papers that address pure network formation models experimentally. Experiments on pure network formation building on the model by Bala and Goyal (2000) are Callander and Plott (2005), Falk and Kosfeld (2012), and Goeree et al (2009), for example. Using the model of Jackson and Wolinsky (1996) as a basis, the laboratory experiment by Kirchsteiger et al (2016), sets its focus on analysing the impact of farsightedness on the ability to reach theoretically predicted stable networks. The experimental research on network formation models mostly confirms the theoretical findings identifying the star, the wheel or the empty network as stable and efficient networks. The only two papers we are aware of that investigate the influence of network disruption in an experiment are Hoyer and Rosenkranz (2015) and Goyal et al (2016). Hoyer and Rosenkranz (2015) test the link disruption introduced in the decentralized model of Hoyer and De Jaegher (2012) in the laboratory. They find that in the treatment with a disruptor, subjects reach the circle network that is the highest paying equilibrium network less often than it would be expected. Goyal et al (2016) conduct a field experiment in which the participants had to choose which other participant to build a link to. They find that under decentralized network formation and network defence facing the threat of contagion from node attacks, the participants form a dense network characterized by centre-protected stars. While using different methods (laboratory vs. field experiment), both of these papers test a model of *decentralized* network formation under the threat of disruption.

In opposition to this, we use the model by Dziubiński and Goyal (2013) as a theoretical foundation for this experiment, which is a *centralized* model of network formation under the threat of node attacks. To the best of our knowledge, there is no other experiment that follows this approach. The theoretical model has clear predictions of the equilibrium network depending on the cost ranges of link formation and node protection.

For rather low costs of link formation and rather high costs of node protection, the equilibrium network is a densely connected network with no protected nodes, whereas for rather low costs of node protection, the equilibrium network is a centre-protected star. While the theory has very clear predictions, what it cannot deliver is showing whether network designers are actually able to reach these networks by building the most efficient networks for different cost levels. Besides this, it gives no indication about the influence of the initial starting network on the network formation process.

We therefore experimentally study the emergence of networks under a known external threat. To be more specific, we deal with the question if subjects are able to form safe and efficient networks while facing a strategic Adversary. This investigation relates theoretical predictions proposed by Dziubiński and Goyal (2013) to actual observed behaviour. Our main objective is to analyse what kind of networks emerge under an external threat and to investigate if subjects are able to build safe and efficient networks. Additionally, subjects face different starting networks, so we can analyse whether the equilibrium networks may be reached from any starting network. Besides investigating the network formation behaviour, we also analyse whether the subjects are able to cause a network disruption by finding and attacking weak spots in the network. Furthermore, the influence of the subjects' farsightedness on their decision-making process is investigated. We find that while in both treatments subjects manage to build predominantly safe networks, efficient networks are built in only one of the two treatments. Furthermore, we find that there is no influence of the starting network on their ability to design safe and efficient networks. Farsightedness –as measured in our experiment– has no influence on subjects' decisions to build safe and efficient networks. However, experience seems to be important, as those students who had experience in any form with network theory before the experiment performed significantly better than their unexperienced counterparts.

The paper is structured as follows: First we describe the experimental set-up including a short review of the underlying theoretical model. Afterwards, we describe the research hypotheses in Section 2. Then we present and discuss the experimental results in Section 3. Finally, Section 4 provides the conclusion.

2 Experiment

2.1 Experimental Design

The theoretical foundation for this experimental analysis is the model of Dziubiński and Goyal (2013). They investigate network formation and disruption by means of node attacks. Their model comprises a sequential-move game in which a Designer first designs a network by building links and allocating perfect defence resources to the nodes knowing about the threat of an attack. Subsequently, an Adversary who has perfect knowledge about the Designer's decisions chooses a number of nodes to attack, whereas his attack budget is exogenously specified. The final network after the attack is called the *residual network*. The model provides insights into preferable network structures given costly links and defence units and a threatening attack: Dziubiński and Goyal (2013) find that for low costs of defence relative to linking, the protection in the network is centralized, the network is sparse, and linking is heterogeneous. For the case of high protection costs relative to linking, the network is dense and linking is homogeneous. In Appendix A we briefly present a formal summary of this model in an already slightly adapted version to our experimental design. In our experimental design we consider networks with $n = 8$ nodes and up to two possible attacks $k_a = 2$ by the Adversary. Due to this relatively high number of nodes, the Designer has many possibilities to design the network. Moreover, it impedes the task insofar that the defence and attack strategies have to be more thoroughly thought through, which reduces the chance of building equilibrium networks out of random link settings.

The network experiment consists of two phases in which two players –the Designer and the Adversary– act sequentially. We randomly match all subjects in groups of two persons for the whole experiment. In Phase I, the Designer is shown four initial starting networks. The Designer designs his networks by setting links and by protecting nodes at cost $c_\ell > 0$ and $c_d > 0$. He builds his networks knowing that the Adversary sees all his formation and protection decisions after Phase I and is allowed to target up to two nodes of each of his networks afterwards. In order to maximize his payoff, the Designer designs the networks to ensure connectivity even after the attacks. Every connected network has the value of $v_D > 0$ Taler for the Designer, from which the costs for links and defence are deducted. Any network that is no longer connected after an attack is worth zero to the Designer (and costs of link formation and protection are ignored). Furthermore, a network is also worth zero to the Designer if he uses all his budget of v_D Taler for the network formation process. Within the experiment, the respective changes in the architecture as well as the potential payoff

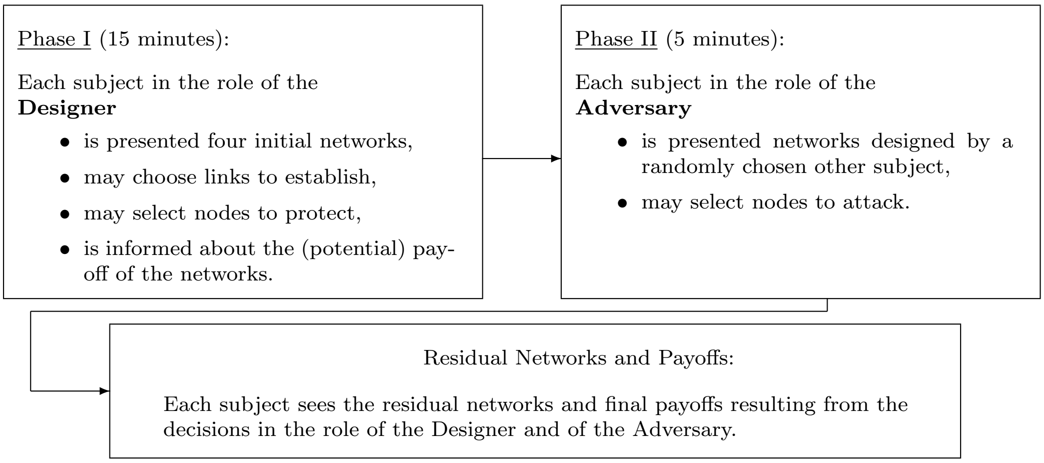
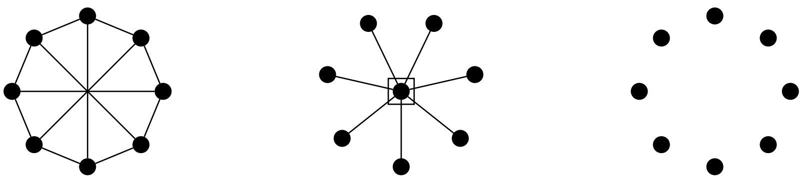


Figure 1: Experimental Design

of the residual network (if it resists the attack of the Adversary) are instantly displayed. For building the networks in Phase I, the Designer has a time restriction of 15 minutes.[1]

There is a vast number of possibilities how the Designer may build a protected network for the given set of nodes. Figure 2 shows some examples for our context with $n = 8$ nodes. In Figure 2(a), the network is an example for a k-connected network with $k = 3$. This means if any set of nodes up to size $k - 1$ is taken out of the network, the residual network is still connected. This k-connected network is also an example for a minimal k-connected network as it has a minimal number of links required for k-connectedness.[2] Figure 2(b) depicts a star with a protected central node linked to any other node by one link. The third network is the empty network containing no links at all, shown in Figure 2(c).



(a) 3-connected network (b) centre-protected star network (c) empty network

Figure 2: Examples for Equilibrium Networks with $n = 8$

The three networks in Figure 2 are of particular importance since exactly these three types of networks actually occur in equilibrium.[3] According to the theoretical model, we define two treatments which can be distinguished by their predicted equilibrium network. More precisely, once the other parameters are fixed, we vary the costs of node protection across the two treatments. Generally, we assume the values of the network to be $v_D = 100$ for the Designer and $v_A = 20$ for the Adversary. In addition, we set the costs of linking to $c_\ell = 5$ and the costs of node protection to $c_d = 20$ for treatment **T1** and to $c_d = 30$ and $c_\ell = 5$ for treatment **T2**. Table 1 summarizes the treatments.

Treatment	**Parameters**						**Equilibrium Network**
	n	k_a	v_D	v_A	c_ℓ	c_d	
T1	8	2	100	20	5	20	centre-protected star network
T2	8	2	100	20	5	30	minimal 3-connected network

Table 1: Treatment Summary

[1]Some preliminary tests have proven this to be an appropriate time restriction. In addition, each subject may individually decide to have finished Phase I earlier and enter into a waiting screen.
[2]For further details on (minimal) k-connectedness see Dziubiński and Goyal (2013).
[3]The according restrictions on the parameters for each network can be found in Appendix A.

For the experiment, we choose to use four initial starting networks, which differ in the placement of the nodes as well as in the initially established links. This allows us to investigate whether the Designer develops an efficient network by following a strategy or has a lucky guess. The position of the starting networks on the screen is arranged randomly per pair of players to avoid any biases through the visual sequence of the networks. Thus, the initial networks are presented to the Designers simultaneously and in random order. Similarly, in Phase II, the Adversary also sees the four designed networks in the same random order and is asked to attack all four of them. This allows us to analyse whether the Adversary is able to strategically attack the networks or if he just randomly picks his targets among the nodes. The initial networks are shown schematically in Figure 3.

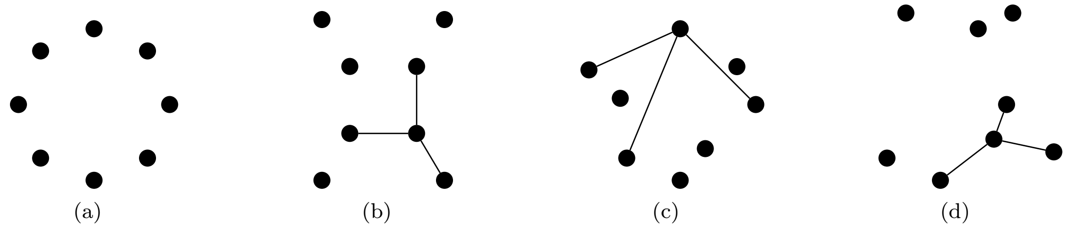


Figure 3: Initial Starting Networks

The initial networks in Phase I consist of the empty network as shown in Figure 3(a) and three other networks as depicted in Figure 3(b) to Figure 3(d). We include the empty network to allow the subjects to freely build links and protect nodes. In each of the other three networks in Figure 3(b) to Figure 3(d), three links are already given and cannot be modified by the subject. However, the costs for the initial links still need to be paid by the Designer. These already included links keep the subjects from simply copying the links they decided on in the empty network to the other presented networks and therefore it requires additional strategic thinking from the subjects. The nodes in Figure 3(a) and Figure 3(b) are displayed in a symmetric array, while in Figure 3(c) and Figure 3(d) there is no particular visible pattern. All networks are shown at the same time on one single screen, which makes it possible for the participants to go back to an already designed network to improve its design and use the experience gained by forming the other networks. Figure 4 shows examples for the equilibrium networks for treatment **T1** and Figure 5 those for treatment **T2**.

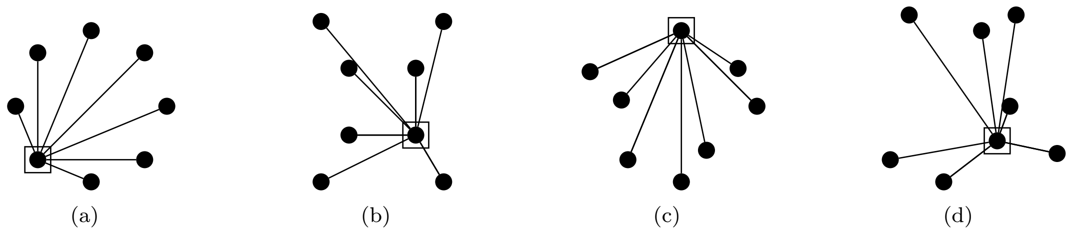


Figure 4: Examples for Equilibrium Networks for Treatment **T1**

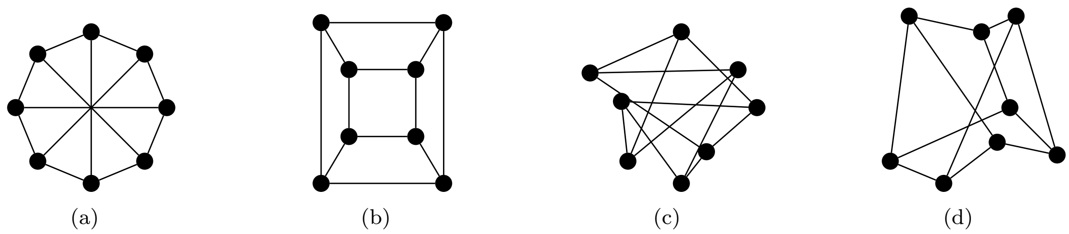


Figure 5: Examples for Equilibrium Networks for Treatment **T2**

We provide monetary incentives for the experiment for which the value of the residual network after the attacks is payoff-relevant.[4] The only modification we make is that once a Designer has spent more for links and node protection than the value of the network, a warning is displayed and the payoff is set to zero. The participants know that they only get paid for two of the eight networks they worked on: The first network the subjects get paid for is one of the four networks they designed. Therefore, their payoff depends on the connectivity of the network after Phase II, since the potential payoff for a connected network is 100 Taler less the costs for linking and protection, and 0 Taler for a disconnected one. The second network they get paid for is one of the four networks they attacked. They earn 20 Taler if the network they attacked is disconnected after Phase II. Their payoff is irrespective of the fact whether the network was already designed in a disconnected manner or whether the network got separated following their attack. For a network which is still connected after the attack, they earn 0 Taler. The complete instructions for the main experiment can be found in Appendix D.1.

Furthermore, the participants' cognitive abilities may matter in the process of finding an equilibrium network. Therefore, we conducted an additional experiment within the questionnaire after the main network formation experiment was finished. This extra experiment addresses the participants' cognitive abilities by using an adaptation of the "11-20 Money Request Game (MRG)" by Arad and Rubinstein (2012). This game tests the subjects' depth of reasoning and gives us a measure for their farsightedness. A detailed description of the game can be found in Appendix C and the additional instructions for the subjects in Appendix D.2.

2.2 Research Hypotheses

The following three hypotheses affect the Designer's network formation behaviour and deal with the equilibrium predictions of the network experiment: Due to the fact that the Designers know about the threat of the subsequent attack, it is generally assumed that they adjust their network formation behaviour to account for this threat. Moreover, since they are even aware of the number of attacks, it is also assumed that the participants are able to form networks which can withstand all of the Adversary's attacks without being disconnected. Summarizing, we expect that the Designers build networks which are safe concerning the Adversaries' attacks. This assumption about the Designers' ability to form safe networks shapes our first hypothesis.

Hypothesis 1 *Independently of the treatment, a significant share of Designers builds safe networks for each initial network.*

According to the theory, the designed networks are expected to be the predicted equilibrium networks. Since the equilibrium networks are also safe networks, it is implied that a significant share of the designed safe networks are equilibrium networks. This means for treatment **T1** that a significant share of safe networks consists of a centre-protected star network and for treatment **T2** that a significant share of safe networks consists of the minimal 3-connected network without defence. Both equilibrium networks are efficient, which means that the payoff for the residual network is maximized given the costs of links and node defence. This definition enables us to differentiate between safe networks and safe networks built with minimal costs –thus networks that are safe and efficient. Consequentially, our second hypothesis directly distinguishes between the emergence of safe, and safe and efficient equilibrium networks.

Hypothesis 2 *Among the safe networks per starting network,*

a) *In treatment **T1**, a centre-protected star network is designed significantly more often than others.*

b) *In treatment **T2**, a minimal* 3*-connected network without defence is designed significantly more often than others.*

The next hypothesis aims at the Designer's personal characteristics and augments the theoretical predictions: Farsightedness might influence the Designer's behaviour. Since forming efficient networks –which cannot be destroyed by the Adversary's two attacks and which at the same time are cost minimal– requires thinking several steps ahead, we conjecture that the Designer's degree of farsightedness plays a role in finding the equilibrium networks. So, Designers are expected to consider the vulnerabilities of their formed networks and take the Adversary's behaviour into account, too. Accordingly, we conjecture that a more farsighted Designer is more effective in building efficient networks. Thus, a participant's degree of farsightedness is expected to positively influence the frequency of equilibrium networks among his designed networks.

Hypothesis 3 *Designers who are more farsighted build the equilibrium networks significantly more often than Designers who are less farsighted.*

[4] See Appendix A for the formal definition of the payoff function.

2.3 Experimental Procedure

Our experiment was conducted in the Business and Economic Research Laboratory (henceforth BaER-Lab) at Paderborn University in February 2017, where it is possible to control potentially confounding factors and observe the network structures without measurement problems (Falk and Kosfeld, 2012). We use the software z-Tree (Fischbacher, 2007) and invite the participating subjects through the online recruitment system Orsee (Greiner, 2015) from a pool of approx. 2,800 voluntary students of Paderborn University from different fields of studies who are enrolled as prospective participants in economic experiments. Subjects are only allowed to participate in one session. Upon arrival each subject is seated randomly at a computer workplace in a cubicle, each detached from one another. All subjects are told not to communicate during the session.

The experiment consists of two parts: The first one is the main network formation experiment, as explained in the previous sections; the second is a follow-up questionnaire to gain additional information on the subjects, in particular on their farsightedness and their risk behaviour. From the MRG, as briefly described previously we deduct steps of reasoning of the participants and use these as a measure of farsightedness. The risk behaviour is measured by two risk assessment questions, which are based on the SOEP (German Socio-Economic Panel Study), and allow us to categorize subjects by their level of risk aversion. Detailed descriptions of the MRG and the risk assessment questions can be found in Appendix C.

All subjects within a treatment receive the same instructions before the experiment and are informed about the structure of the experiment and the payoffs associated with designing and attacking the networks.[5] The subjects have 15 minutes to read the five pages of instructions on their own. Afterwards, the main points of the instructions are repeated verbally by the experimentor. Before starting the experiment, all participants are asked to complete a control questionnaire consisting of five questions about the details of the experiment to ensure their understanding. At the end of the network formation experiment, one of the participating subjects is randomly chosen to roll a dice to determine the network position relevant for the final monetary payment for all subjects. Note that the networks are displayed in random order per group of subjects. This means that typically the initial networks relevant for the final monetary payments vary among groups. We set the exchange rate to 1 Euro for 5 Taler and the show-up fee to 5 Euro.[6] Each session took about 65 minutes, including time to read the instructions and receiving the payoff. In total, there were 96 subjects in the experiment. These participants generated an average payment of 13.28 Euro (including 5 Euro as a show-up fee). In the first treatment, 48 subjects attended with an average payment of 13.90 Euro; in the second treatment, 48 subjects took part generating an average payment of 12.67 Euro.

3 Results

In this section we present the main findings. Table 2 shows a summary of our data across both treatments, concerning the age, gender and semester of studies. The majority of subjects (86%) did not have previous experience with network theory. As our experiment was conducted in German, we did not ask for nationality because our subject pool consisted of mainly German students. In addition to the general summary statistics, in Table 2 we also include data on the level of reasoning of the subjects as elicited in the MRG and on the mean overall risk aversion as elicited in the questionnaire (see Appendix C for further information). For the mean level or reasoning, we have between 0 and 11 steps, where 11 is very farsighted and 0 is not farsighted at all. For risk aversion, we have 11 categories between 0 and 10, where 10 is very risk averse and 0 is very risk loving.

The descriptives in Table 3 concern the networks that our subjects designed in the experiment. It shows a summary of the networks designed in the two treatments given the different starting networks. Here (a) to (d) refers to the different initial starting networks as depicted in Figures 2(a) to 2(d). In Table 3 we summarized which networks were designed, differentiating by their resistance against attacks and by their architecture. Regarding resistance against attacks, we consider as *safe* networks those networks that could not be disconnected by deleting up to two nodes. Correspondingly, *unsafe* networks are those that could be disconnected by such an attack. For the distinction by network architecture, the *CPS* and *Minimal* 3 refer to the centre-protected star and the minimal 3-connected network without defence. These two networks are the

[5] In the instructions we used the words *design* and *separate* a network, to avoid any influence of the more suggestive terms of *attacking* a network.

[6] We chose this rather high show-up fee, as there was a chance that students did not earn anything in the experiment. This applied if they did not built a safe network that was then destroyed by their partner and did not destroy their partner's network themselves.

Variable	Treatment T1	Treatment T2	Total Sample
Male	46%	27%	36%
Mean Age	23.77	24.56	24.17
Mean Semester	5.04	5.38	5.21
Experience Networks	17%	10%	14%
Mean Farsightedness	2.83	3.23	3.03
Mean Risk Aversion	5.31	5.58	5.44

Table 2: Summary Statistics

equilibrium networks for treatment **T1** and **T2**, respectively. In addition, we also consider those networks which were already built disconnected in Phase I by the Designer and denote them as *Designed disconnected*. The remaining networks are then summarized as *Other networks*. Please note that per treatment per starting network we have 48 observations.

Number of:	Treatment T1				Treatment T2			
	Starting Network							
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
Total Networks	48	48	48	48	48	48	48	48
Networks by Resistance against Attacks:								
Safe Networks	34	30	31	33	28	28	28	27
Unsafe Networks	14	18	17	15	20	20	20	21
Networks by Architecture:								
CPS	30	27	30	31	21	17	24	21
Minimal 3	1	0	0	0	5	4	3	3
Designed Disconnected	8	9	10	8	5	4	7	4
Other Networks	9	12	8	9	17	23	14	20

Table 3: Overview of Built Networks

In order to determine whether the share of Designers who built safe networks is significant independent of starting network, as proposed in Hypothesis 1, we first conduct a χ^2-test to analyse whether the amount of safe networks built depends on the starting network. For treatment **T1** we find a χ^2-statistic of 0.9375; for treatment **T2** we find a χ^2-statistic of 0.0641 and neither is significant at $p < 0.05$. Therefore, we conclude that there is no difference between starting networks in the ability of Designers to build safe networks. We then conduct a Wilcoxon signed rank test to analyse whether a significant share of Designers manages to build a safe network, independent of starting network. Here we find a z-value of 2.670, which is significant at $p < 0.01$. Result 1 follows from this. Support for Result 1 is also provided by Table 3, which presents the amount of safe networks, and row one of Table 4. In addition, we also see evidence for Result 1 in the distribution of the observed payoffs per starting network and treatment, which can be found in in Appendix B.1.

Result 1 *A significant share of Designers manages to build a safe network, independent of starting network.*

Looking more into detail who managed to design safe networks, a χ^2-test shows, not surprisingly, that the 13 subjects who had experience with network analysis did significantly better than the remaining subjects in terms of building safe and efficient networks, for $p < 0.1$ and $p < 0.01$ respectively.[7] Interestingly, the ability to design safe networks, while not depending on a starting network as such, still does not mean that a subject who once managed to build a safe network could achieve this in all four of his networks. Out of the 49 subjects who were able to build at least one safe network, only 51% managed to build all

[7] A first observed gender effect in the ability to build safe networks is rescinded, when also taking experience with network analysis into account.

four networks as safe. Thus, it seems that some additional strategic thinking by the subjects is required to transfer the knowledge of how to build a safe network to all possible starting networks. In addition to the subjects' experience with networks, we also look at the influence of their risk aversion on the ability to design safe or safe and efficient networks. We measured risk aversion by means of asking students to self-assess their risk attitude in two questions at the end of the experiment.[8] Using a Jonckheere-Terpstra test we find no statistically significant relationship between the degree of risk aversion and the underlying observed behaviour of forming safe (z-value $= 0.5665$, $p > 0.1$) or safe and efficient networks (z-value $= 0.4335$, $p > 0.1$).

	Number of Subjects who successfully designed (out of 4):					**Wilcoxon test**
	0	1	2	3	4	
Safe Networks	25	6	9	9	47	$z = 2.670^{***}$
CPS Networks	24	2	4	4	24	$z = -5.088^{***}$
Min3 Networks	42	2	1	1	2	$z = 4.366^{***}$
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.						

Table 4: Safe and Efficient Networks per Subject

Looking at the safe networks per treatment, it can directly be deducted from Table 3 that the CPS is built more often than the minimal 3-connected network for both treatments. Interestingly, the few times that subjects managed to design the minimal 3-connected network was in treatment **T2**, where it was also efficient to do so (see also Table 5). In order to test whether in treatment **T1** the CPS is designed more frequently than other safe networks and whether in treatment **T2** the minimal 3-connected network is designed more frequently than other safe networks, we conduct a Wilcoxon signed rank test for each of the two treatments. For treatment **T1** we find that among the safe networks the CPS is designed significantly more often than others with a z-value of -5.088 for a $p < 0.01$. For treatment **T2** we find that among the safe networks the minimal 3-connected network is *not* designed more often than other safe networks. Here the test actually indicates that other safe networks are designed significantly more often than the minimal 3-connected network, with a z-value of 4.366 for $p < 0.01$. Results 2a and 2b follow from this. Support for Results 2a and 2b is also provided in rows 2 and 3 of Table 4, respectively.

Result 2a *The centre-protected star network is designed significantly more often than others in treatment **T1**.*

Result 2b *The minimal* 3*-connected network is* not *designed significantly more often than others in treatment **T2**.*

Since the CPS seems to be the more intuitive solution for most subjects, we also tested whether it was designed more often in treatment **T1**, where it was also efficient, than in treatment **T2**, where it was safe but not efficient. Here we use a χ^2-test and find that the CPS is designed significantly more often in treatment **T1** than in treatment **T2**. We also find that the minimal 3-connected network was designed significantly more often in treatment **T2** than in treatment **T1**. Thus, while it seems to have been difficult for the subjects to design a minimal 3-connected network, they succeeded to do so significantly more often in the treatment where it was also the efficient solution. Support for this can be found in Table 5. Additionally, we also analysed whether our results are robust to taking in account networks that are *almost* minimal 3-connected networks.[9] Qualitatively the results are in line with the results presented here. Details can be found in Appendix B.2.

Finally, we also analyse the impact of Designers' farsightedness on their ability to build equilibrium networks. Here we use the MRG, as introduced by Arad and Rubinstein (2012), giving us a measure for the farsightedness of our subjects. Subjects could request an integer amount between 11 and 20 Euro. If their requested amount was exactly one less than the amount their partner requested, they could get an additional 20 Euro.[10] The distribution of answers in our MRG is remarkably similar to the one found in

[8]The questions and instructions can be found in Appendix C.
[9]These are networks where subjects seem to have wanted to design a minimal 3-connected network, but did not quite manage to do so. The exact definition of these networks can be found in Appendix B.2.
[10]After the experiment, in each session a group number was chosen for whom the MRG was actually paid out.

Treatment	CPS	Not CPS	Min3	Not Min3
T1	118	74	1	191
T2	83	109	15	177
χ^2	12.7885***		12.7826***	
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.				

Table 5: CPS and Minimal 3-connected Networks per Treatment

Arad and Rubinstein (2012). Most students can be categorized as having level 1-, 2- or 3-reasoning, thus requesting 19, 18 or 17 Euro.[11] After the MRG, we also asked subjects to write down why they chose a certain amount of money, and by means of their answers we corrected the level k-reasoning deducted from the MRG.[12] We do not find an ascending trend with the Jonckheere-Terpstra test which would support our hypothesis that subjects who exhibit more farsightedness are more likely to form efficient networks. For this farsightedness measure we find, however, that there is simply no relation between farsightedness and the number of efficient networks designed with $p = 0.8663$ for the ascending trend test and $p = 0.1337$ for the descending trend test.[13] This insignificant relationship cannot be explained by risk preferences, as we find no correlation between the measures of farsightedness and risk aversion in our sample (Kendells Tau value of -0.0680, p-value of 0.3779).

Result 3 *The level of Designers' farsightedness does not concur with their ability to build equilibrium networks.*

Additionally, we also look at the subjects' ability to destroy networks when being in the role of the Adversary. Each subject in Phase II of the experiment got to attack up to two nodes in the networks his partner constructed in Phase I. As a lot of the networks had been built in such a way that no successful attack was possible (see Table 3), only few subjects had the possibility to actually attack a network successfully. Out of the 384 networks designed in the experiment only 105 networks were destroyable; out of these, 73 were actually destroyed by the Adversary. The remaining 32 networks could have been destroyed by an attack on two nodes, but the Adversaries were not successful in finding and attacking the weak spots of the network. We use this as a control to test whether those subjects who were able to destroy a network, if they had the chance to do so, were also more successful in designing efficient networks. However, we do not find that this is the case. Using a χ^2-test, we find that there is no significant relation between the ability to build safe and/or efficient networks and the ability to successfully destroy a network if one has the chance to do so. It has to be taken into account, though, that overall there were not a lot of subjects who actually had the chance to destroy networks, therefore this may not be a very accurate measure.

4 Conclusion

In this paper we report results from an experiment in which subjects play a network formation game knowing that the network will be attacked afterwards. The game is modelled on the theoretical results by Dziubiński and Goyal (2013). We find that while subjects are overall able to build networks that are safe against the subsequent attack, independent of their starting network, they only manage to build efficient networks in treatment **T1**, where the efficient network is the centre-protected star. In treatment **T2**, where the efficient network is a minimal 3-connected network, the large majority of subjects failed to design this network. However, we show that those subjects who do manage to design a minimal 3-connected network do so in treatment **T2**, where it is also the efficient network.

Interestingly, in contrast to previous, often decentralised network formation experiments, we do not find that more symmetric networks are built more often (see, for example, Falk and Kosfeld 2012). On the

[11] Interestingly, among our 48 groups, there were 8 groups in which one person requested exactly 1 Euro less than the other person. In these groups the lower requesting partner requested 18 Euro in most cases, 17 Euro in one case and 16 Euro in one case.

[12] Thus, for example, people requesting 13 Euro, who report that they did this because the 13th is their birthday, are put to level 0-reasoning instead of the level 7-reasoning they are coded as in the pure MRG.

[13] Looking at the values of the pure MRG, we find that there is actually a negative relationship between level k-reasoning and the ability to build safe and efficient networks. This can be seen from the results of the Jonckheere-Terpstra test, which has a p-value of 0.9791 when testing for an ascending trend between subjects' farsightedness and the number of equilibrium networks they designed. Instead, we find a significant descending trend for the variables, with $p < 0.05$.

contrary, we find that network Designers tend to build the (centre-protected) star network significantly more often than the more symmetric minimal 3-connected network. It seems that while in decentralized models of network formation the asymmetric payoffs to the centre and the spokes of the star prevent this network from being built, in a centralized model the (centre-protected) star is the most intuitive solution. The minimal 3-connected network, on the other hand, seems to be too complicated for the majority of subjects to be built. This is surprising, as it can be designed as a very symmetric network.

We find that farsightedness, as measured by the MRG, does not predict well which subjects build efficient and safe networks. While we find that students with any kind of experience with network theory do significantly better than their inexperienced counterparts, we neither find significant differences in other personality characteristics such as gender nor do we find that the degree of risk aversion is related with building efficient and safe networks.

Overall, it seems to be the case that subjects are in principal able to understand the network formation game and manage to build safe networks. However, for some cost structures building efficient networks is already too complex in an environment where a network consists of only eight nodes and payoffs are calculated on-the-fly for the subjects while designing the network. Additionally, subjects have ample time to try out different designs and can also go back to change their previously made designs, but still in treatment **T2**, most of them fail to reach a minimal 3-connected network. Also, only approximately half of those subjects who build at least one safe network manage to build safe networks for all four starting networks. Thus, there seems to be an additional complexity involved in transferring the way to build a safe network from one starting network to another. However, these complexities can be overcome by using more experienced subjects, as can be seen from our finding that subjects with any sort of former introduction to network theory did significantly better.

One possible extension of the current analysis is motivated by Landwehr (2015), who studies network formation behaviour in case of imperfect node as well as link defence. By that, he extends the model of Dziubiński and Goyal (2013), who only considered perfect defence as protection against node attacks. Here the predicted equilibrium networks change and, due to the increased complexity of the model, the set of networks gets less symmetric. It would be interesting to test in an experiment if subjects are still able to build these new equilibrium networks, even with this increased complexity. To test this, a new experiment is needed, as networks consisting of 8 nodes would probably be already too much of a challenge for the subjects and the parameters for equilibrium networks also need to be adjusted.

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Appendix

A Theory

The sequential game has two players: a Designer and an Adversary. The Designer makes his decision during the first phase and then the Adversary decides.

In the first phase, the Designer chooses a strategy to build and protect a network for a fixed set of n nodes ($n \geq 3$). In other words, the Designer decides which nodes he links at a constant and exogenously given cost c_ℓ, with $c_\ell > 0$ and which nodes he protects at an exogenously given cost c_d, with $c_d > 0$. A protected node cannot be removed from the network by an attack of the Adversary. We denote the strategy which the Designer has chosen by the pair (g, δ), which consists of the network g described by a set of links and the set of protected nodes by δ.[14]

In the second phase, the Adversary sees the designed and protected networks and decides which nodes to attack. If the Adversary decides to attack a node that is not protected, this node and all its links are removed from the network. If the node is protected, the Adversary's attack has no impact on the network. Let $k_a > 0$ denote the maximal number of attacks the Adversary is allowed to choose. Attacks are assumed to be costless. Let the (sub)set of nodes that the Adversary chooses to attack be denoted by X. The final network after the attack is called the *residual network*. It is connected if every pair of nodes either directly has a link between them, or if they are indirectly linked via other nodes. A network which is not connected is disconnected.

The payoffs are as follows

$$\pi^D(g, \delta, X) = \begin{cases} v_D - |\delta| \cdot c_d - |g| \cdot c_\ell & \text{if the residual network is connected,} \\ 0 & \text{if the residual network is not connected.} \end{cases}$$

$$\pi^A(g, \delta, X) = \begin{cases} 0 & \text{if the residual network is connected,} \\ v_A & \text{if the residual network is not connected.} \end{cases}$$

with $v_D, v_A > 0$. The parameters v_D and v_A indicate the value of the residual network.[15] Intuitively, as long as the costs for links and protection are not too high, it is the Designer's goal to design a network at minimum costs that cannot be attacked by the Adversary, while the goal of the Adversary is to destroy the Designer's network.

Proposition 1 (see Dziubiński and Goyal, 2013) *Assume $k_a \leq n - 2$.*

In equilibrium the Designer builds a protected network (g, δ) such that

- *for $c_\ell < v_D / \left\lceil \frac{n(k_a+1)}{2} \right\rceil$ and $c_d > c_\ell \left(\left\lceil \frac{n(k_a-1)}{2} \right\rceil + 1 \right)$ it is a minimal $(k_a + 1)$-connected network,*
- *for $c_\ell (n-1) + c_d < v_D$ and $c_d < c_\ell \left(\left\lceil \frac{n(k_a-1)}{2} \right\rceil + 1 \right)$ it is a centre-protected star network,*
- *otherwise g is the empty network and no node is protected, $\delta = \emptyset$.*

In equilibrium, the Adversary chooses -if possible- a set such that the network is no longer connected and, if it is not possible to disconnected the network, any set of nodes yields the same payoff.

Important underlying assumptions in this model are the perfect information about the network, its structure and its characteristics such as the cost structure and the player's objectives and payoffs. Moreover, the defence of nodes is perfect. Thus, unprotected nodes are removed with certainty after an attack and a protected node remains in the network even after being targeted. Regarding the attack, it is assumed that the Adversary's budget is exogenously given. In addition, the Adversary's budget is perfectly known by the Designer and the Adversary attacks the network optimally given that he observes the designed network.

[14] Formally, given a finite set of nodes $N = \{1, ..., n\}$ with $n \geq 3$, a network g is a set of links, i.e., $g \subseteq \{\{i, j\} | i, j \in N, i \neq j\}$ and a set of protected nodes is a (sub)set of nodes, i.e., $\delta \subseteq N$.

[15] For scaling purposes in the experimental design we model the utility functions here such that the values v_D and v_A are not necessarily identical. Note that in the model of Dziubiński and Goyal (2013), these values were supposed to be identical and for the formal analysis set to be equal to 1. Formally, the values of the residual network are a mapping associating to every possible residual network a value for the Designer and for the Adversary. For notational simplification, we omit this dependence on the residual network here.

B Experimental Results

B.1 Observed Payoffs

Figures 6 and 7 show the observed payoffs of the Designer after the attack of the Adversary in Phase II.

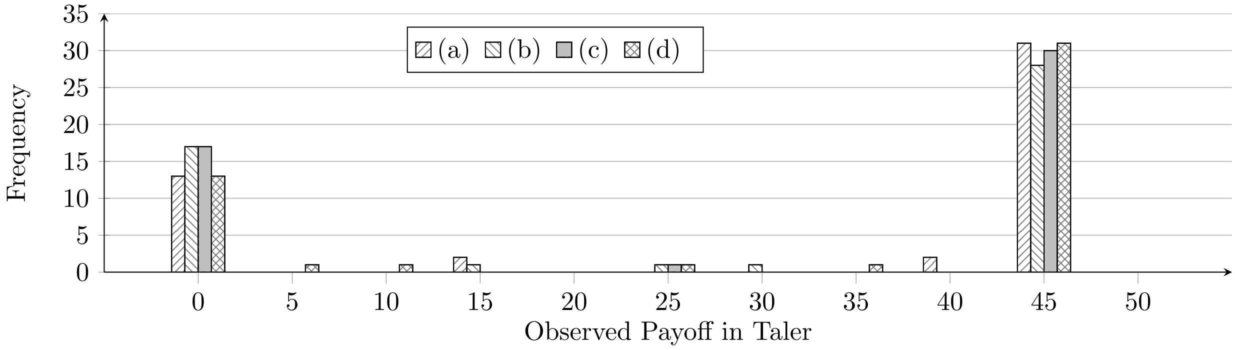


Figure 6: Observed Payoffs for Treatment **T1** by Starting Network

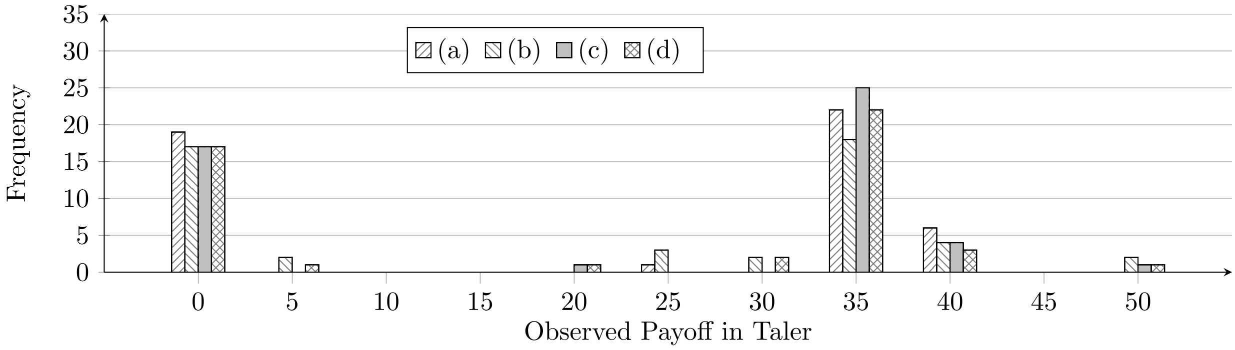


Figure 7: Observed Payoffs for Treatment **T2** by Starting Network

Note that the payoff from the theoretical predictions for treatment **T1** is equal to 45 Taler for the centre-protected star network and for treatment **T2** this is 40 Taler for the minimal 3-connected network. The payoff for the centre-protected star network in treatment **T2** is 35 Taler and the payoff is zero whenever the network was successfully disconnected by the Adversary (or already disconnected before the attack) or all the budget was used to build the network. Payoffs larger than the equilibrium payoffs indicate that while the network could have been disconnected during the attack, the Adversary did not manage to do so.

B.2 Robustness

As the minimal 3-connected network seems to have been a less intuitive network to design for the subjects, as a robustness check we analyse whether our results are affected if we assume that those networks where subjects managed to build *almost minimal 3-connected networks* are analysed as minimal 3-connected. The reason for this is that there are a number of networks where it seems that subjects tried to build a minimal 3-connected network, but failed in achieving this and added one or two additional links to the network. Therefore, we defined networks to be almost minimal 3-connected when they are safe against disruption, each node has at least 3 links, no protection is used, and maximally 14 links are used in the network. Using this definition, we find 7 networks that are almost minimal 3-connected.[16] Adding the almost minimal 3-connected to the minimal 3-connected and replicating Table 5, we obtain Table 6.

[16]That our reasoning seems to hold can also be deduced from the fact that there are no almost minimal 3-connected networks for starting network 1, which is the empty network. Since no links were previously given in this network, everyone who wanted to build a minimal 3-connected network also managed to do so.

Treatment	CPS	Not CPS	(Almost) Min3	Not (almost) Min3
T1	118	74	2	190
T2	83	109	21	171
χ^2	12.7885***		16.6957***	
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.				

Table 6: CPS and (almost) Minimal 3-connected Networks per Treatment

It can be seen from Table 6 that those subjects that build almost minimal 3-connected networks do so in treatment **T2**, where the minimal 3-connected network was also the efficient solution. Henceforth, we briefly present this model in an already slightly adapted version to our experimental design. For a comprehensive description and analysis of the underlying theoretical model we refer to Dziubiński and Goyal (2013).

C Questionnaires to Elicit Further Information

Money Request Game (see Arad and Rubinstein, 2012). The Money Request Game (henceforth MRG) is rested on level-k models, which assume that persons can be clustered into different groups regarding their depth of reasoning. For example, a level-0 type person would act non-strategically and thinks no step ahead of his own behaviour. In our version of the MRG, the participants are matched in groups of two and have to choose an amount between 11 and 20 Euro, which they get paid at the end. They have the opportunity to additionally gain 20 Euro if their chosen amount is exactly 1 Euro less than the partner's requested amount, which is supposed to encourage to think about the partner's strategy. This enables us to categorize participants by different levels of reasoning, corresponding to the number they state in the game. After the participants stated their amount, they are asked to explain their numeric decision. At the end, one of the groups gets randomly chosen to be paid their stated amounts from the game. You may find the English translation of the instructions you may find in Appendix D.2.

Questionnaire Including Risk Assessment. The final part of the experiment is a personal questionnaire. The questionnaire aims at gaining insights about the subjects' personal characteristics as well as their strategic behaviour: Thus, their network formation and network disruption strategies are asked. By means of this information, we are able to better understand their decision-making process and see if the subjects formed their networks randomly or according to a specific strategy. Moreover, it is asked if they have had any experience with network theory. This would be likely to improve their understanding and their results in the network formation and attacking process.

Generally, it is uncontroversial that the participants' risk attitude influences their decisions within an experiment (Dohmen et al, 2010, Harrison and Rutström, 2008). Thus, we include two questions into the questionnaire in which the participants have to self-assess their risk behaviour in certain situations. The risk assessment questions are based on the SOEP (German Socio-Economic Panel Study), which is a large panel dataset with the aim to represent the German population introduced by a professional surveying company. Since the SOEP is very extensive and includes a large spread of issues, we chose just questions 4 and 125 from the panel in the year 2014, which both aim specifically at the participants' risk attitudes (TNS Infratest Sozialforschung 2014). The first question is an all-around measure of the participants willingness to take risks in general. Hence, this first question asks participants if they are rather risk averse or not. Since average willingness to take risks varies across contexts, the second question deals with risk in specific contexts: It is asked about their risk behaviour in financial issues, at driving, in sports and leisure, on the job, regarding their personal health status, and regarding trusting unknown persons. For both questions, participants can choose values on a scale from 0 to 10, whereas 0 means "not willing to take risk at all", and 10 means "very willing to take risk". We choose these questions because they suit our purpose to collect information about the participants' risk attitudes in a simple way. Moreover, the second, more detailed question serves to rule out potential inconsistencies in self-estimation and is a direct measurement of the participants' risk attitudes and the inexpensiveness to collect the information (Dohmen et al, 2011). Besides, Dohmen et al (2011) confirm these questions to be a fit measurement of subjects' risk self-assessment by conducting a mixture of experiment and survey and use the survey to validate the participants' risk attitudes measured in the earlier conducted experiment.

D Instructions (English Version)

The version of the instructions presented in this section is a translation of the original instructions written in German. Variations between the two treatments are indicated in square brackets. The instructions for the MRG are close to the ones of Arad and Rubinstein (2012).

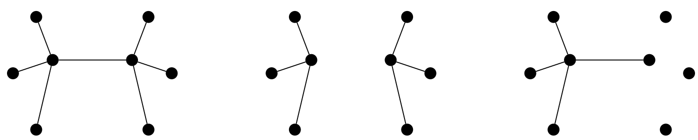
D.1 Experiment Instructions

General information

- During the experiment all payments are stated in the fictitious currency "Taler".
- After the experiment we would like to ask you to fill out a questionnaire. For this you will receive a short instruction as soon as the experiment has ended.
- In addition to the instructions you also receive a separate explanation of the computer screen.

Structure of the experiment

- This experiment consists of two phases: Phase I and Phase II.
- The experiment is about networks. Examples for networks are electricity networks, transport systems, communication systems and oil pipelines.
- A network is displayed in this experiment by points and links between these points.
- A network is said to be **connected**
  - if all existing points form one network; this means that each point has a link to at least one of the other points and that in a connected network there are no points without any links and there are no separate sub-networks.
- A network is **disconnected**
  - if there is at least one point in the network that is not connected by a link to the other points. This implies that the network is disconnected if the existing network is separated into several sub-networks or single points are isolated.
- The next figure (schematically) shows examples for connected and disconnected networks:



Example connected network

Example disconnected network (with two sub networks)

Example disconnected network with one sub-network and three isolated points

Course of the experiment

Phase I (design networks)

- For Phase I (design networks) you have 15 minutes (900 seconds).
- Initially, you see four networks in which in some there are already existing links.
- Every network shall be considered separately and independent of the other networks.
- The network currently chosen to work on is marked by a green frame on the computer screen (see separate explanation of the computer screen).

Your task is to design in total four networks for the four initial starting networks.

Note that in Phase II (remove points) of the experiment a different participant may remove two points from each of your networks.

Your payment per network is dependent on the connectedness of the network after Phase II.

- You have two possibilities when designing your networks: You may establish links or protect points. You cannot protect links.
- Establishing links and protecting points is costly:
  - Establishing a link between two points costs **5 Taler**.
  - Protecting a point costs **20 Taler** *[for treatment **T2** protecting points costs **30 Taler**].*

  At most you can spend 100 Taler per network. This means that you cannot establish infinitely many links and/or protect all points.
- The additional links may be established between two points for which there is no initial link. Initial links cannot be deleted and the costs for these links are deduced from your budget.
- All points may be protected. Protected points are marked by a square around the point.
- You cannot add additional points. All existing points need to be included in the network, otherwise the network counts as disconnected.
- After the design is finished, you are asked to click on "Continue" to proceed with the experiment.

Phase II (remove points)

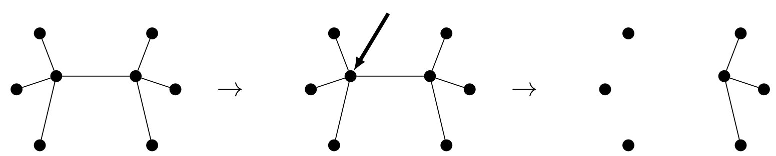
- For Phase II (remove points) you have 5 minutes (300 seconds).
- You see four networks of **another participant**. You see them as they have been designed by the other participant in Phase I.
- Every network shall be considered separately and independent of the other networks.

Your task is to remove up to **two points** from each of the four networks .

- If you decide to remove a protected point, this has no impact on the network. Neither the protection nor the point itself will be removed.
- If you decide to remove an unprotected point, this point and all its adjacent links will be removed. The network is reduced by this point, but may not necessarily be disconnected. As long as all remaining points are connected with at least one link, the network remains connected with a smaller number of points.

Your payment per network is dependent on the connectedness the network of the other participant after Phase II.

- Links can only be removed indirectly together with unprotected points. Links cannot be removed separately from the network.
- The decision to remove protected and/or unprotected points has **no costs**.



Connected network after Phase I → Unprotected point for removal selected → Disconnected network after Phase II

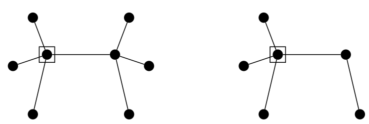
Payments

- Your payment consists of two parts: You receive a payment for one of the networks that you designed in Phase I and for one of the networks from which you removed points in Phase II.
- The payment-relevant network is determined after the experiment by means of one randomly chosen participant rolling a dice.
- For the payment only the remaining networks after Phase II are going to be considered.
- The payment of the networks depends on the related task.
  - For the networks you designed (Phase I), you receive a potential payment for connected networks. This means that if after Phase II a network is
    - **disconnected**, your potential payment for this network is 0 Taler. You are charged no costs for the links and protection of points.
    - **connected**, your potential payment for this network is 100 Taler less the costs for the established links, the initial links and the protected points.
  - For networks in which you removed points (Phase II), you receive a potential payment for disconnected networks. This means that if after Phase II one of the networks in which you removed points is
    - **disconnected**, your potential payment for this network is 20 Taler.
    - **connected**, your potential payment for this network is 0 Taler.
- The currency Taler will be converted with an exchange rate of 2.00 Euro per 10 Taler. The payment is paid in cash together with a show-up fee of 5.00 Euro.

Examples for the payment

Example 1

after Phase I after Phase II



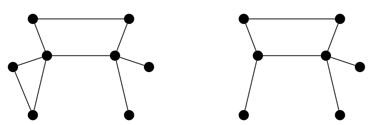
Number of links: 7
Number of protected points: 1
Costs: 35 Taler + 20 Taler = 55 Taler

Number of removed points: 2
Status of the network: connected

Payment for the network designer:
100 Taler – 55 Taler = 45 Taler
Payment for the point-remover: 0 Taler

Example 2

after Phase I after Phase II



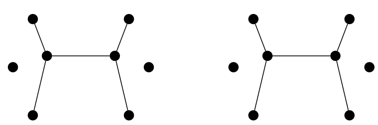
Number of links: 9
Number of protected points: 0
Costs: 45 Taler

Number of removed points: 1
Status of the network: connected

Payment for the network designer:
100 Taler – 45 Taler = 55 Taler
Payment for the point-remover: 0 Taler

Example 3

after Phase I after Phase II



Number of links: 5
Number of protected points: 0
Costs: 25 Taler

Number of removed points: 0
Status of the network: disconnected

Payment for the network designer: 0 Taler
Payment for the point-remover: 20 Taler

*[Please note, for **T2** the costs for protection are* 30 *Taler, and the calculations change accordingly.]*

Please note:

- During the entire experiment, any and all forms of communication is not permitted.
- All mobile phones must be switched off during the entire duration of the experiment.
- The decisions you make within this experiment are anonymous: i.e., none of the other participants gets to know the identity of a person who has made a specific decision.
- Please remain seated until the end of the experiment. You will be called forward for your payment by your seat number.

Good luck and thank you very much for your participation in this experiment!

D.2 Instructions Money Request Game

The experiment is over now. We proceed with the questionnaire.

Instructions questionnaire part 1:

- In part 1 of the questionnaire, we would like to know how you decide when you have the possibility to request an amount of money.
- More precisely, you are in the following situation:

  "You and another participant play a game, in which you request an amount of money. The amount of money needs to be an integer between 11 and 20 Euro. You may only select numbers in steps of 1. You and the other participant will receive the amount requested. One of you will receive an additional 20 Euro if he asks for exactly one Euro less than the other participant. What amount of money do you request?"

- Thus, you may chose a number and enter this number in the display box.
- Afterwards, you will be asked to explain your decision.

Additional profit opportunity in part 1 of the questionnaire:

- In the first part of the questionnaire you have another chance to win a payment.
- For this, one group of two participants in this room will be drawn randomly.
- The group will be selected by chance: A random participant will draw one of the group numbers.
- The number which was drawn will be passed through the room silently, in order for all participants to see the number.
- You will be informed on the computer screen about your group and whether you have won.
- The selected group receives the additional payment, one of them potentially the additional 20 Euro and the payment for the main experiment after the completion of the final part of the questionnaire.

Upon the completion of the first part of the questionnaire by all participants, **part 2** will follow. The answers in part 2 are irrelevant for the payment.

All questions will be evaluated anonymously and communication is not allowed during the complete experiment.

Thank you very much for the participation in this experiment!