APPLIED MECHANISM DESIGN FOR SOCIAL GOOD

JOHN P DICKERSON

Lecture #13 – 3/10/2020

CMSC828M
Tuesdays & Thursdays
2:00pm – 3:15pm

COMPUTER SCIENCE
UNIVERSITY OF MARYLAND

PROJECT PROPOSALS

I'd like you to submit a 1-2 pager covering an initial plan for your course project by the end of the week.

How to submit:

- Make a channel on Slack (public or private)
- Invite all group members + @John Dickerson
- Upload the PDF of your initial course project plan
- "@ me"

You will get 100% for this if you submit something "okay" – this is just to kickstart (i) movement and (ii) discussion between us

PROJECT PROPOSALS: A SUGGESTION

Consider a 75%/100%/125% set of goalposts:

Project Plan:

75% goals

- Create and train 3 regressor system for electrical energy consumption dataset.
- Design the adaptive learning algorithm.

100% goals

- Implement the adaptive learning algorithm.
- Apply the algorithm to forecasting electrical energy consumption in the United States problem.
- Compare its performance with baselines which are:
  - Single regressor agent.
  - Multi-agents with equal weights.

125% goals

- Compare this algorithm performance against other techniques used to improve long horizon forecast.
- Test this algorithm performance on other forecasting problems including a forecasting brain ventricular volume as a biomarker for neurodegenerative disease progression.
- Test performance on other decision making problems that are unrelated to forecasting.

[Thanks, Aya Ismail! S2018 CMSC828M]

THIS CLASS: STACKELBERG & SECURITY GAMES

Thanks to: AGT book, Conitzer (VC), Gupta (NG), Procaccia (AP)

SIMULTANEOUS PLAY

Previously, assumed players would play simultaneously

- Two drivers simultaneously decide to go straight or divert
- Two prisoners simultaneously defect or cooperate
- Players simultaneously choose rock, paper, or scissors
- Etc …

No knowledge of the other players' chosen actions

What if we allow sequential action selection ...?

LEADER-FOLLOWER GAMES

Heinrich von Stackelberg

Two players:

- **The leader commits to acting in a specific way**
- **The follower observes the leader's mixed strategy**

NE, iterated strict dominance

Commit to "Bottom"	
0, 0	2, 1

What is the Nash equilibrium ????????

- **Social welfare: 2**
- **Utility to row player: 1**

Row player = leader; what to do ????????

- **Social welfare: 3**
- **Utility to row player: 2**

ASIDE: FIRST-MOVER ADVANTAGE (FMA)

From the econ side of things …

- **Leader is sometimes called the Market Leader**
- **Some advantage allows a firm to move first:**
  - Technological breakthrough via R&D
  - Buying up all assets at low price before market adjusts

By committing to a strategy (some amount of production), can effectively force other players' hands.

Things we won't model:

- Significant cost of R&D, uncertainty over market demand, initial marketing costs, etc.

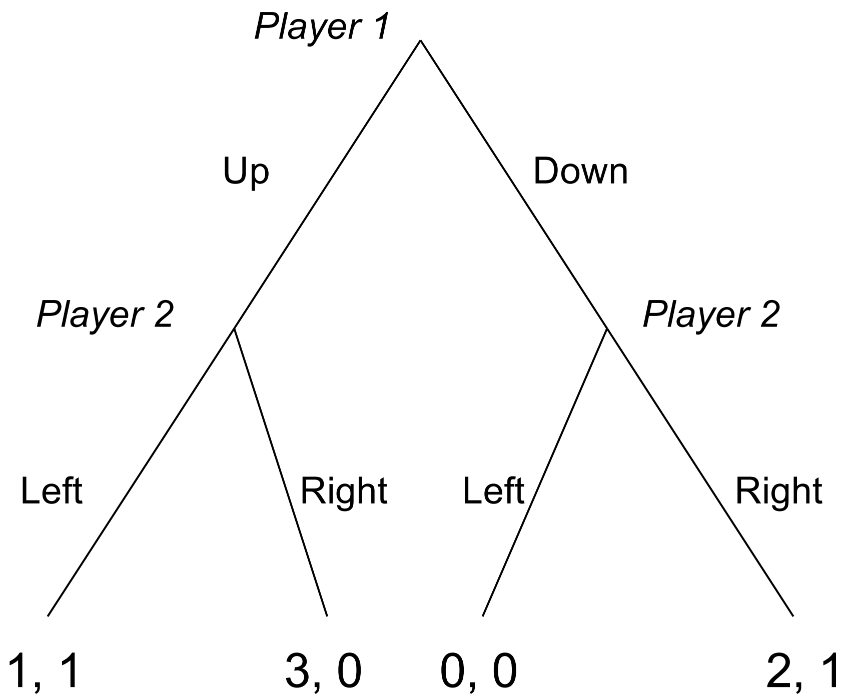
These can lead to Second-Mover Advantage

- **Atari vs Nintendo, MySpace (or earlier) vs Facebook**

COMMITMENT AS AN EXTENSIVE-FORM GAME

1, 1	3, 0
0, 0	2, 1

For the case of committing to a pure strategy:



COMMITMENT TO MIXED STRATEGIES

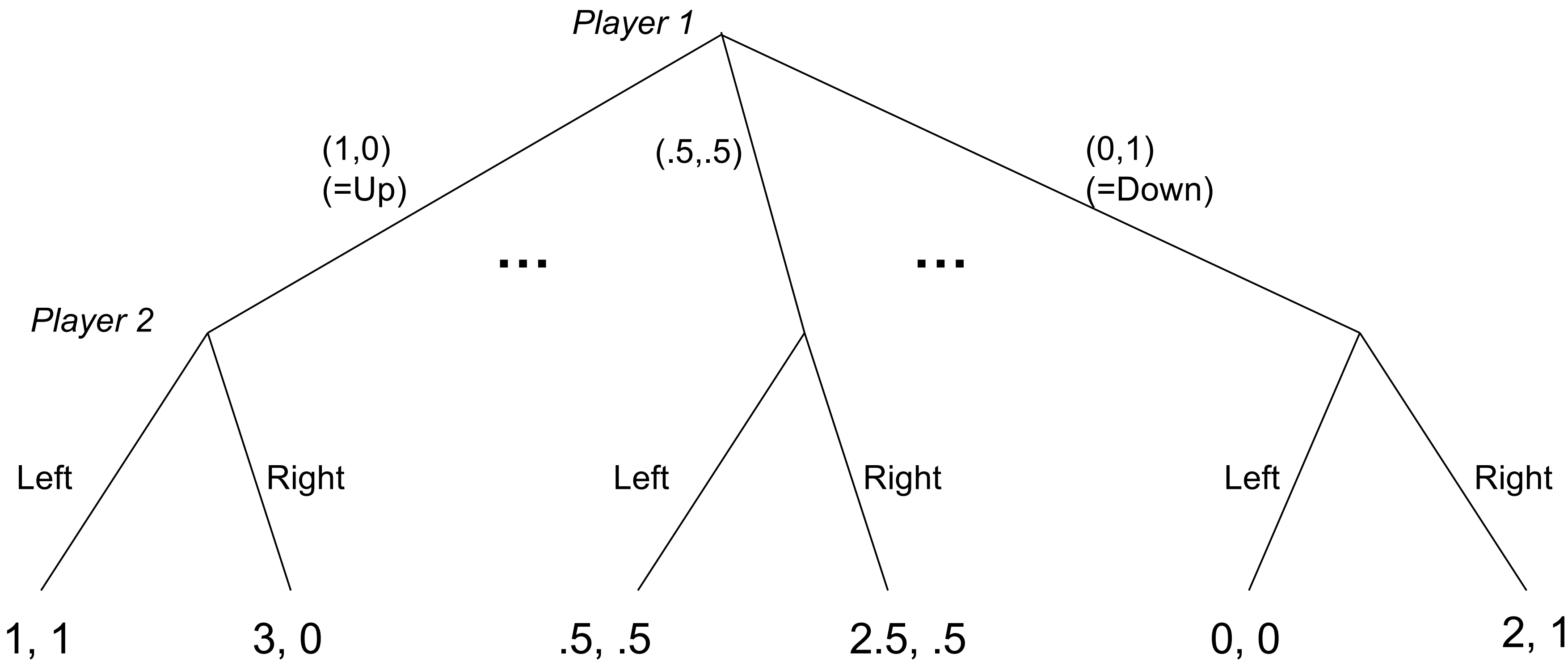
	0	1
.49	1, 1	3, 0
.51	0, 0	2, 1

What should Column do ????????

Sometimes also called a Stackelberg (mixed) strategy

COMMITMENT AS AN EXTENSIVE-FORM GAME…

For the case of committing to a mixed strategy:



- **Economist: Just an extensive-form game …**
- **Computer scientist: Infinite-size game! Representation matters**

WHAT SHOULD THE LEADER COMMIT TO?

2-P
Z-S

Special case: 2-player zero-sum normal-form games

Recall: Row player plays Minimax strategy

- **Minimizes the maximum expected utility to the Col**
- **Minimax utility: $\min_{\sigma_{-i}} \max_{s_i} u_i(s_i, \sigma_{-i})$**

Doesn't matter who commits to what, when

Minimax strategies = Nash Equilibrium

= Stackelberg Equilibrium

(not the case for general games)

Polynomial time computation via LP – earlier lectures

WHAT SHOULD THE LEADER COMMIT TO?

2-P
G-S

Strong Stackelberg Equilibrium (SSE): follower breaks ties in favor of the leader

Theorem [Conitzer & Sandholm]: In 2-player, general-sum normal-form games, an SSE can be found in polytime

- **?????????????**

Idea:

- **Iterate over every follower pure strategy aka column c**
- **Compute a mixed strategy r for leader such that playing pure strategy c is a best response for follower**
- **Choose r*, the best (aka highest value for leader) mixed strategy amongst those strategies!**

[Conitzer & Sandholm, Computing the optimal strategy to commit to, EC-06]

WHAT SHOULD THE LEADER COMMIT TO?

2-P
G-S

Separate LP for every column c^*:

$$\textit{maximize } \Sigma_r \, p_r \, u_R(r, c^*)$$

Row utility

s.t.

$$\textit{for all } c,\ \Sigma_r \, p_r \, u_C(r, c^*) \geq \Sigma_r \, p_r \, u_C(r, c)$$

Column optimality
aka Col best response

$$\Sigma_r \, p_r = 1$$

$$\textit{for all } r,\ p_r \geq 0$$

Distributional constraints

Choose strategy from LP with highest objective

[Conitzer & Sandholm, Computing the optimal strategy to commit to, EC-06]

RUNNING EXAMPLE

x	1, 1	3, 0
y	0, 0	2, 1

maximize $1x + 0y$

s.t.

$1x + 0y \geq 0x + 1y$

$x + y = 1$

$x \geq 0$

$y \geq 0$

maximize $3x + 2y$

s.t.

$0x + 1y \geq 1x + 0y$

$x + y = 1$

$x \geq 0$

$y \geq 0$

IS COMMITMENT ALWAYS GOOD FOR THE LEADER?

Yes, if we allow commitment to mixed strategies

- Always weakly better to commit [von Stengel & Zamir, 2004] **??????**
- If (r^*, c) is Nash, then Row can always commit to r^* → Col will play c^*, can achieve value of that equilibrium

What about only pure strategies?

Expected utility to Row by playing mixed Nash:
???????????

$\mathbf{E_R[\langle 1/3,1/3,1/3 \rangle] = 0}$

Expected utility to Row by any pure commitment:
???????????

$\mathbf{E_R[\langle 1,0,0 \rangle] = -1}$
$\mathbf{E_R[\langle 0,1,0 \rangle] = -1}$
$\mathbf{E_R[\langle 0,0,1 \rangle] = -1}$

	Rock	Paper	Scissors
Rock			
Paper	+1,-1	0,0	-1,+1
Scissors			

WHAT SHOULD THE LEADER COMMIT TO?

Bayesian
2-P G-S

Bayesian games: player *i* draws type θ_i from Θ

Special case: follower has only one type, leader has type θ

Like before, solve a separate LP for every column c*:

$$\textit{maximize } \Sigma_\theta \pi(\theta)\ \Sigma_r\, p_{r,\theta}\, u_{R,\theta}(r, c^*)$$

$$\textit{s.t.}$$

$$\textit{for all } c,\ \Sigma_\theta \pi(\theta)\, \Sigma_r\, p_{r,\theta}\, u_C(r, c^*) \geq \Sigma_\theta \pi(\theta)\, \Sigma_r\, p_{r,\theta}\, u_C(r, c)$$

$$\textit{for all } \theta,\ \Sigma_r\, p_{r,\theta} = 1$$

$$\textit{for all } r,\theta,\ p_{r,\theta} \geq 0$$

Choose strategy from LP with highest objective

WHAT SHOULD THE LEADER COMMIT TO?

Bayesian
N-P G-S

So, we showed polynomial-time methods for:

- **2-Player, zero-sum**
- **2-Player, general-sum**
- **2-Player, general-sum, Bayesian with 1-type follower**

In general, NP-hard to compute:

- **2-Player, general-sum, Bayesian with 1-type leader**
  - Arguably more interesting ("I know my own type")
- **2-Player, general-sum, Bayesian general**
- ***N*-Player, for *N* > 2:**
  - 1st player commits, *N*-1-Player leader-follower game, 2nd player commits, recurse until 2-Player leader-follower

STACKELBERG SECURITY GAMES

Leader-follower → Defender-attacker

- Defender is interested in protecting a set of targets
- Attacker wants to attack the targets

The defender is endowed with a set of resources

- Resources protect the targets and prevent attacks

Utilities:

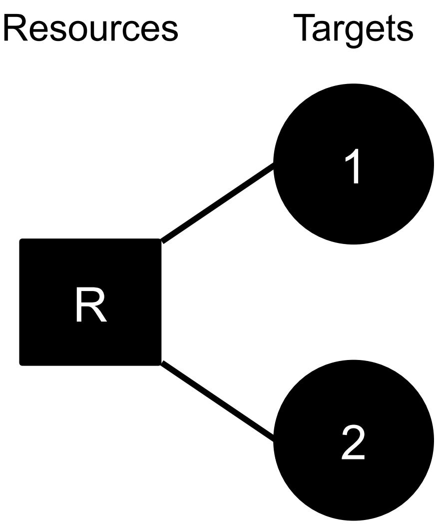
- Defender receives positive utility for preventing attacks, negative utility for “successful” attacks
- Attacker: positive utility for successful attacks, negative otherwise
- Not necessarily zero-sum

SECURITY GAMES: A FORMAL MODEL

Defined by a 3-tuple (N, U, M):

- **N: set of *n* targets**
- **U: utilities associated with defender and attacker**
- **M: all subsets of targets that can be simultaneously defended by deployments of resources**
  - A schedule $S \subseteq 2^N$ is the set of target defended by a single resource *r*
  - Assignment function $A : R \rightarrow 2^S$ is the set of all schedules a specific resource can support
- **Then we have *m* pure strategies, assigning resources such that the union of their target coverage is in M**
- **Utility $u_{c,d}(i)$ and $u_{u,d}(i)$ for the defender when target i is attacked and is covered or defended, respectively**

SIMPLE EXAMPLE



Targets	Defender		Attacker Type θ_1		Attacker Type θ_2	
i	**$u_{c,d}(i)$**	**$u_{u,d}(i)$**	**$u_{c,a}(i)$**	**$u_{u,a}(i)$**	**$u_{c,a}(i)$**	**$u_{u,a}(i)$**
1	0	-1	0	+1	0	+1
2	0	-2	0	+5	0	+1

[Blum, Haghtalab, Procaccia, Learning to Play Stackelberg Security Games, 2016]

REAL-WORLD SECURITY GAMES

Lots of deployed applications!

- Checkpoints at airports
- Patrol routes in harbors
- Scheduling Federal Air Marshalls
- Patrol routes for anti-poachers

Typically solve for strong Stackelberg Equilibria:

- Tie break in favor of the defender; always exists
- Can often “nudge” the adversary in practice

Two big practical problems: computation and uncertainty

OVERVIEW OF AN IMPACTFUL PAPER IN THIS SPACE [Kiekintveld et al. 2009]

Computing Optimal Randomized Resource Allocations for Massive Security Games (linked on course webpage)

- Motivated first by resource assignment for checkpoints at LAX, e.g., multiple canine units assigned to cover multiple terminals …
- … and later by much larger games such as Federal Air Marshals Service assignments and port inspection.

m resources to cover n targets, m < n

Defender (leader) commits to a mixed strategy

Attacker (follower) observes the probabilities for each coverage set

- Surveillance, insider threat, etc – maybe not perfectly realistic

Attacker chooses a pure strategy

Equilibrium concept not ex post

OVERVIEW OF AN IMPACTFUL PAPER IN THIS SPACE [Kiekintveld et al. 2009]

Initially assume interchangeable resources (extended in paper, won't cover here)

Assume players are risk neutral

One type of follower (attacker)

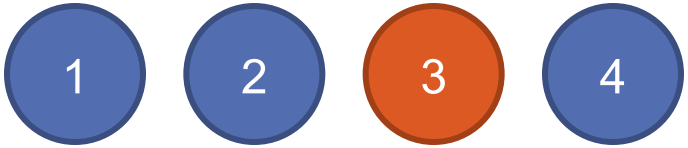
- Recall: one type of follower → PTIME solvable, one LP solved for each pure strategy of follower …
- … but the number of pure strategies in some games might be large, e.g., with 100 targets and 10 resources, 1.7×10^{13}!

RUNNING EXAMPLE

4 targets, 2 resources

Qualitatively:

- Defender values all 4 targets equally (and prefers a covered attack to an uncovered attack).
- Attacker gets twice as much utility for successful attack on target 3. All failed attacks get the same (lower) utility.



MOTIVATION AND INTRODUCTION

1 2 3 4

"Utility for leader θ if the target 3 is attacked and it is covered (c) or uncovered (u)"

$u^{c}_{\Theta}(3)$ $u^{u}_{\Theta}(3)$

Targets {1, 2, 4}		
	Covered	Uncovered
Defender	4	1
Attacker	0	1

Target 3		
	Covered	Uncovered
Defender	4	1
Attacker	0	2

"Utility for follower Ψ if attacks target 3 and it is covered (c) / uncovered (u)"

$u^{c}_{\Psi}(3)$ $u^{u}_{\Psi}(3)$

COMPACT REPRESENTATIONS OF SECURITY GAMES—EXTENSIVE FORM IS TOO BIG!

Defender commits to a mixed strategy (one of uncountably many, i.e., EFG tree will be infinite size)

$$\left.\begin{aligned} \Delta = (\delta_{12}, \delta_{13}, \delta_{14}, \delta_{23}, \delta_{24}, \delta_{34}) \\ \forall i,j \ 0 \leq \delta_{ij} \leq 1 \end{aligned}\right\} \text{In general, size } \binom{n}{m}$$

$$\sum_{i,j} \delta_{ij} = m$$

Attacker strategy is an efficient algorithm, which given any mixed strategy, Δ, computes target $\arg \max_{t \in \Gamma(\Delta)} U_\Theta(\Delta, t)$

Where optimization is taken over the attack set Γ(Δ), the set of targets yielding max expected payoff for attacker given Δ

$$\Gamma(\Delta) = \{t : t \in \arg\max U_\Psi(\Delta, t)\}$$

COMPACT REPRESENTATIONS OF SECURITY GAMES

Key insight: the only information needed to represent the defender strategy is the probabilities a target is covered

$$\delta_{\Theta}^{1,2} + \delta_{\Theta}^{1,3} + \delta_{\Theta}^{1,4} = c_1$$
$$\delta_{\Theta}^{1,2} + \delta_{\Theta}^{2,3} + \delta_{\Theta}^{2,4} = c_2$$
$$\delta_{\Theta}^{1,3} + \delta_{\Theta}^{2,3} + \delta_{\Theta}^{3,4} = c_3$$
$$\delta_{\Theta}^{1,4} + \delta_{\Theta}^{2,4} + \delta_{\Theta}^{3,4} = c_4$$

In our 2 resources, 4 targets example: probability c_1 that target 1 is covered is sum of all pure strategies that cover 1

This gives us a coverage vector C

- Running example: C = [c_1, c_2, c_3, c_4]

ERASER (Efficient Randomized Allocation of SEcurity Resources) **takes security game & computes C that is SSE for defender**

ERASER FORMULATION

$$
\begin{aligned}
\max \quad & d & \\
a_t \in \quad & \{0,1\} & \forall t \in T \\
\sum_{t \in T} a_t = \quad & 1 & \\
c_t \in \quad & [0,1] & \forall t \in T \\
\sum_{t \in T} c_t \leq \quad & m & \\
d - U_\Theta(t, C) \leq \quad & (1 - a_t) \cdot Z & \forall t \in T \\
0 \leq k - U_\Psi(t, C) \leq \quad & (1 - a_t) \cdot Z & \forall t \in T
\end{aligned}
$$

Attacker can assign mass to exactly one target

Defender applies valid (aka at most m) probability mass over targets

$$U_\Theta(t, C) = c_t U_\Theta^c(t) + (1 - c_t) U_\Theta^u(t)$$

(Theorem in paper states how to convert coverage vector to mixed strategy)

ERASER FORMULATION

$$
\begin{aligned}
\max \quad & d \\
a_t \in \quad & \{0,1\} \qquad \forall t \in T \\
\sum_{t \in T} a_t = \quad & 1 \\
c_t \in \quad & [0,1] \qquad \forall t \in T \\
\sum_{t \in T} c_t \leq \quad & m \\
d - U_\Theta(t,C) \leq \quad & (1-a_t)\cdot Z \qquad \forall t \in T \\
0 \leq k - U_\Psi(t,C) \leq \quad & (1-a_t)\cdot Z \qquad \forall t \in T
\end{aligned}
$$

Expected utility to leader given attack on t and coverage vector with coverage c_t

$$U_\Theta(t,C) \quad = \quad c_t U^c_\Theta(t) + (1-c_t) U^u_\Theta(t)$$

Determine the defender's expected payoff d, given the target attacked (a_t)

- **For unattacked targets (a_t=0), RHS is huge (i.e., Z)**
- **For attacked target (a_t=1), RHS is 0 → d = utility of defender given t attacked, and coverage vector C**

Objective: maximize d

ERASER FORMULATION

$$
\begin{aligned}
\max \quad & d & \\
a_t \in \quad & \{0,1\} & \forall t \in T \\
\sum_{t \in T} a_t = \quad & 1 & \\
c_t \in \quad & [0,1] & \forall t \in T \\
\sum_{t \in T} c_t \leq \quad & m & \\
d - U_\Theta(t, C) \leq \quad & (1 - a_t) \cdot Z & \forall t \in T \\
0 \leq k - U_\Psi(t, C) \leq \quad & (1 - a_t) \cdot Z & \forall t \in T
\end{aligned}
$$

Two bottom sets of constraints imply that defender's coverage vector C is best response to attack vector A, & vice versa

→ Strong Stackelberg Equilibrium

"Big M" (or in this case "Big Z") style of constraints are a common way to encode if statements

ERASER: RUNNING EXAMPLE (2 RESOURCES, 4 TARGETS)

$$
\begin{aligned}
\max d& \\
s.t.& \\
& \\
a_1 + a_2 + a_3 + a_4 &= 1 \\
c_1 + c_2 + c_3 + c_4 &\leq m \\
d - 4c_1 + (c_1 - 1) &\leq (1 - a_1)Z \\
d - 4c_2 + (c_2 - 1) &\leq (1 - a_2)Z \\
d - 4c_3 + (c_3 - 1) &\leq (1 - a_3)Z \\
d - 4c_4 + (c_4 - 1) &\leq (1 - a_4)Z \\
0 \leq k + c_1 - 1 &\leq (1 - a_1)Z \\
0 \leq k + c_2 - 1 &\leq (1 - a_2)Z \\
0 \leq k + 2c_3 - 2 &\leq (1 - a_3)Z \\
0 \leq k + c_4 - 1 &\leq (1 - a_4)Z \\
c_t &\in [0, 1] \\
a_t &\in \{0, 1\}
\end{aligned}
$$

ERASER: RUNNING EXAMPLE (2 RESOURCES, 4 TARGETS)

```
Elapsed time = 0.01 sec. (0.26 ticks, tree = 0.01 MB, solutions = 3)

Root node processing (before b&c):
  Real time             =    0.01 sec. (0.26 ticks)
Parallel b&c, 4 threads:
  Real time             =    0.00 sec. (0.00 ticks)
  Sync time (average)   =    0.00 sec.
  Wait time (average)   =    0.00 sec.
                          ------------
Total (root+branch&cut) =    0.01 sec. (0.26 ticks)

Solution status =  101 : MIP_optimal
Solution value  =  3.14285714286
Row 0:  Slack =   0.000000
Row 1:  Slack =   0.000000
Row 2:  Slack =  99.142857
Row 3:  Slack =  99.142857
Row 4:  Slack =   0.000000
Row 5:  Slack =  99.142857
Row 6:  Slack =   0.000000
Row 7:  Slack =   0.000000
Row 8:  Slack =   0.000000
Row 9:  Slack =   0.000000
Row 10:  Slack = 100.000000
Row 11:  Slack = 100.000000
Row 12:  Slack =   0.000000
Row 13:  Slack = 100.000000
Column 0:  Value =   3.142857
Column 1:  Value =  -0.000000
Column 2:  Value =  -0.000000
Column 3:  Value =   1.000000
Column 4:  Value =   0.000000
Column 5:  Value =   0.428571
Column 6:  Value =   0.428571
Column 7:  Value =   0.714286
Column 8:  Value =   0.428571
Column 9:  Value =   0.571429
Coverage vector: [0.428571428571, 0.428571428571, 0.714285714286, 0.428571428571]
Adversary attack vector: [-0.0, -0.0, 1.0, 0.0]
mb_pro_umd:mech ngupta$
```

$$c_1 = c_2 = c_4 = 3/7$$
$$c_3 = 5/7$$

ERASER – RUNNING EXAMPLE

$$\delta_{12} + \delta_{13} + \delta_{14} = 3/7$$
$$\delta_{12} + \delta_{23} + \delta_{24} = 3/7$$
$$\delta_{13} + \delta_{23} + \delta_{34} = 5/7$$
$$\delta_{14} + \delta_{24} + \delta_{34} = 3/7$$
$$0 \leq \delta_{12} \leq 1$$
$$0 \leq \delta_{13} \leq 1$$
$$0 \leq \delta_{14} \leq 1$$
$$0 \leq \delta_{23} \leq 1$$
$$0 \leq \delta_{24} \leq 1$$
$$0 \leq \delta_{34} \leq 1$$

$$\Rightarrow$$

$$\delta_{12} = \delta_{14} = \delta_{24} = 2/21$$
$$\delta_{13} = \delta_{23} = \delta_{34} = 5/21$$