

# Incentive-compatible Social Choice

Boi Faltings  
Swiss Federal Institute of  
Technology (EPFL)

# Social Choice

Choose an outcome  $o \in \{o_1, \dots\}$  that  
a set of agents  $A_1, \dots, A_k$  agree on

Examples:

- How to share airspace, radio spectrum, power lines, etc.
- Public policy decisions
- Dividing an inheritance
- ...



# Social Choice Mechanisms

Mechanism:

protocol that chooses an outcome

Goals:

- Efficiency: maximize agents' combined utility (payoff)
- Individual rationality: each agent is better off participating than not

# Commonly used Mechanisms

- Round-robin:
  - ignores differences
- Lotteries:
  - suboptimal outcome
- Voting:
  - limited to simple decisions

Can we do better with computers?

# Outline

- Example: slot allocation
- Optimizing social choice
- A truly incentive-compatible mechanism
- Incentive-compatible coordination

# Example: Slot Allocation

- Airport runway can take only 1 plane/minute: 1 slot/minute
- Allocation:
  - what slot requests are granted?
- Coordination constraints:
  - flight needs takeoff and landing slot at different airports
  - flights need to be in sequence (rotation)

# Current System

Slots are free

Allocation (each airport):

- 75% : historical rights to reuse same slots
- 25%: given on request in round-robin fashion, taking into account airline size

Coordination:

- IATA scheduling conferences (2/year)

# Does it work?

- Demand exceeds capacity by up to 40%, but...
- 25% of allocated slots unused!
- Lack of coordination:
  - = > Airlines do not fly the best schedules
  - = > Poor service to the public!

# Outline

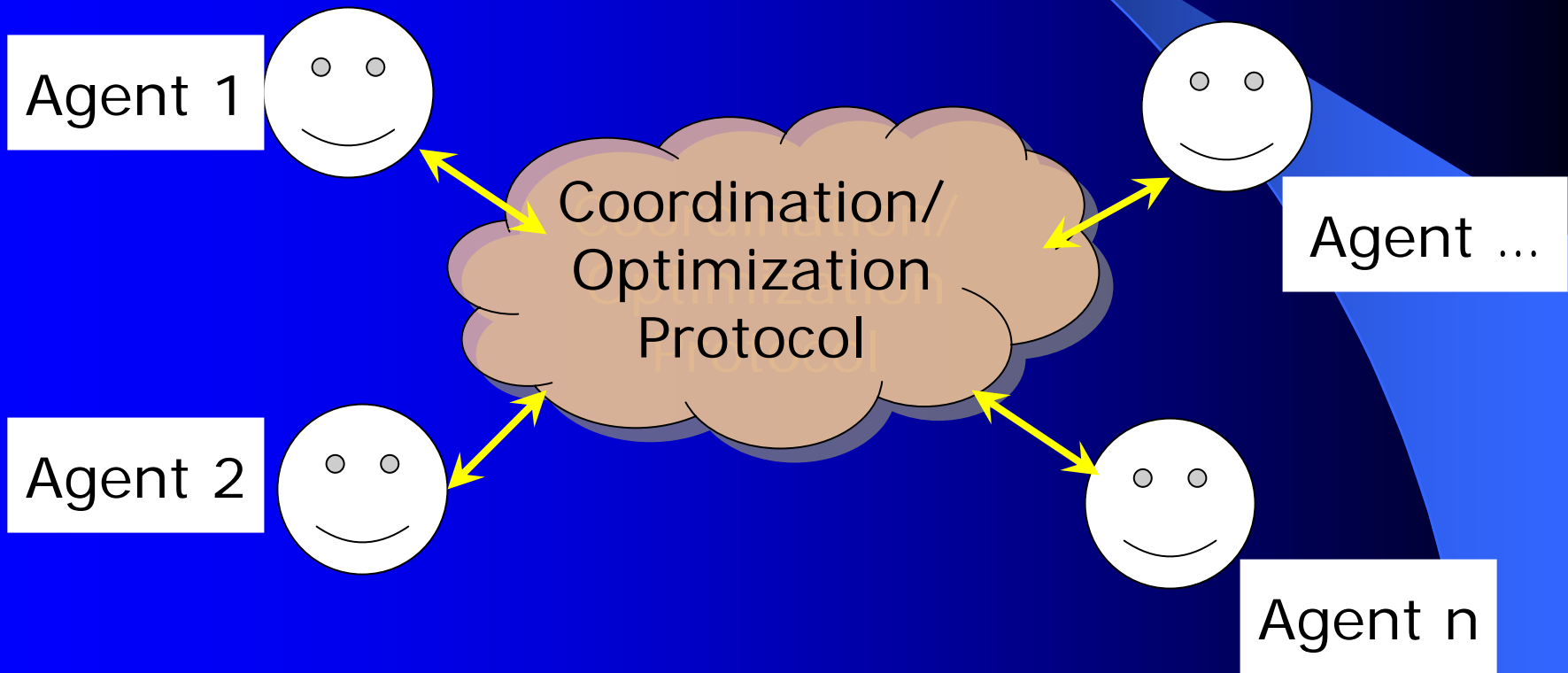
- Example: slot allocation
- *Improving social choice*
- A truly incentive-compatible mechanism
- Incentive-compatible coordination

# Improving Social Choice

- Optimization: choose allocation to optimize economic value
  - Coordination: allocate matching pairs/sequences of slots
- = > multi-agent problem-solving

# Agent-based Social Choice (Coordination)

Preference/Constraint Elicitation



# EPFL results...

## Distributed Constraint Satisfaction:

- AAS + successors (Silaghi, 2000)
- Breakout (Eisenberg, Petcu, 2003)

## Preference/Constraint Elicitation:

- Open Constraint Programming (Macho-Gonzalez, 2002)
- Example-critiquing (Torrens, Pu, ..., 1997-2004)

## Applications:

- Communication networks (Willmott, Calisti, 1998-2001)
- Project coordination (Eisenberg, 2002)

# Incentive-compatibility

Agents have conflicting incentives  
=> do not cooperate for best solution



Social choice mechanism should make  
incentives *compatible*:

=> agents are best off by cooperating

# Simple social choice

- Agents communicate their utility for each outcome
- Algorithm chooses outcome that maximizes sum of the utilities
- Centralized or distributed protocols

# Example

- Airport has 2 slots
- 4 airlines  $A_1$ - $A_4$  want to use a slot
- They value its utility as follows:

$A_1$	$A_2$	$A_3$	$A_4$
10	8	3	1

# Choosing a solution

Maximize sum of values:

- $A_1$  and  $A_2$  get the slots

= >  $A_3, A_4$  would exaggerate their utilities!

= > coordination and optimization make no sense!

# Auctions



- Charge a variable fee for each slot
- English auction: increase fee until demand = supply

$A_1$	$A_2$	$A_3$	$A_4$
10	8	3	1

$\Rightarrow A_1, A_2$  can fly; each pays  $\$3(+\varepsilon)$   
Give revenue ( $\$6$ ) to airport

# Incentive-compatibility

IC mechanism makes equivalent:

- optimizing agent's own utility
- optimizing combined utility

Auction achieves IC for airlines:

only agents with highest valuations  
have interest in winning auction

# Incentives



If a runway is “closed for maintenance”:

- only  $A_1$  gets a slot
- how much does it pay?

$A_1$	$A_2$	$A_3$	$A_4$
10	8	3	1

$\$8(+\varepsilon) > \$6$ : airport revenue increases!

$\Rightarrow$  bad service is rewarded

# Incentive-compatibility

- Auction is incentive-compatible for airlines, but not for airports!



- Right incentive: airport has no revenue from auction, but only from fees

# An Impossible Objective?

Game theory:

impossible to simultaneously have:

- Budget-balance (no revenue/loss)
- Incentive compatibility
- Individual rationality
- Efficiency (optimality)

# Proposals

- DaGVA: return to each agent its *expected* payment (known in advance) [d'Aspremont & Gerard-Varet, 1979]
- Automated mechanism design: design a mechanism for a specific situation [Sandholm, 2003]
- Approximate IC, etc... [Parkes et al., 2001]

# Outline

- Example: slot allocation
- Optimizing social choice
- *A truly incentive-compatible mechanism*
- Incentive-compatible coordination

# Revenue-free Auctions

Solution: give up optimality

- choose one agent to be excluded
- auction slots among remaining agents
- give revenue to excluded agent
- excluded agent chosen independently of declarations (random, round-robin, etc.)

# Example

$A_1$  excluded  $\Rightarrow$  valuations:

$A_1$	$A_2$	$A_3$	$A_4$
10	8	3	1

$\Rightarrow A_2, A_3$  get a slot; each pays \$1 (+ $\epsilon$ )  
Give revenue (\$2) to  $A_1$

## Example (2)

Left out	Winners	Payment
$A_1$	$A_2, A_3$	$2 * \$1$
$A_2$	$A_1, A_3$	$2 * \$1$
$A_3$	$A_1, A_2$	$2 * \$1$
$A_4$	$A_1, A_2$	$2 * \$3$

# Expected Outcomes

Airline	P(slot)	E[Payment]
$A_1$	$\frac{3}{4}$	\$ $\frac{3}{4}$
$A_2$	$\frac{3}{4}$	\$ $\frac{3}{4}$
$A_3$	$\frac{1}{2}$	0
$A_4$	0	- 2 * \$ $\frac{3}{4}$

Assumption: each agent left out with  $p=1/4$

# Properties

- Incentive-compatible for airlines:
  - A excluded: declarations do not matter
  - A included: equal to auction
- Individually rational for airlines:
  - A excluded: receives payment
  - A included: equal to auction
- Incentive-compatible for airport:
  - Best service optimizes income

## Properties (2)

- Solution is suboptimal:
  - $E[\text{Utility}] = 15$  instead of 18
- But auctions not optimal either:
  - Total airline utility =  $18 - 6 = 12$
- Utility almost always better than auctions!

# Outline

- Example: slot allocation
- Optimizing social choice
- A truly incentive-compatible mechanism
- *Incentive-compatible coordination*

# Coordination

Allocation of available slots:  
variables  $x_1, \dots, x_n$

Only certain combinations are  
usable: constraints  $c_i(x_j, x_k, \dots)$

Slot combinations have commercial  
value: relations  $r_i(x_j, x_k, \dots)$

# Formalizing Social Choice

Constraint optimization problem (COP)  
 $\langle X, D, C, R \rangle$ :

- $X$  = set of  $n$  variables (choices)
- $D$  = set of  $n$  domains (options)
- $C$  = set of  $m$  constraints (restrictions)
- $R$  = set of  $p$  relations (valuations)
- Relations belong to agents  $A_1, \dots, A_k$ :  
 $R_i = R(A_i), R = \cup R_i$

# Efficient Solution

$V^*_R(X)$  = assignment to  $X$  that

- satisfies all constraints
- maximizes sum of utilities in  $R$

# Incentive-compatibility...

- "Auction" mechanism  $\Rightarrow$  VCG tax:

$$\text{Pay}(A_i) = \sum_{j \neq i} R_j(V_{R \setminus R_i}^*) - R_j(V_R^*)$$

("damage" to others)

- Incentive-compatible: agents best off to declare their true relations

# Revenue-free VCG Tax

As in revenue-free auction:

- Choose excluded agent  $A_e$
- Others optimize outcome
- Pay VCG tax to excluded agent:

$$\text{Pay}(A_i \rightarrow A_e) =$$

$$\sum_{j \neq i, e} R_j(V_{R \setminus (R_i \cup R_e)}^*) - R_j(V_{R \setminus R_e}^*)$$

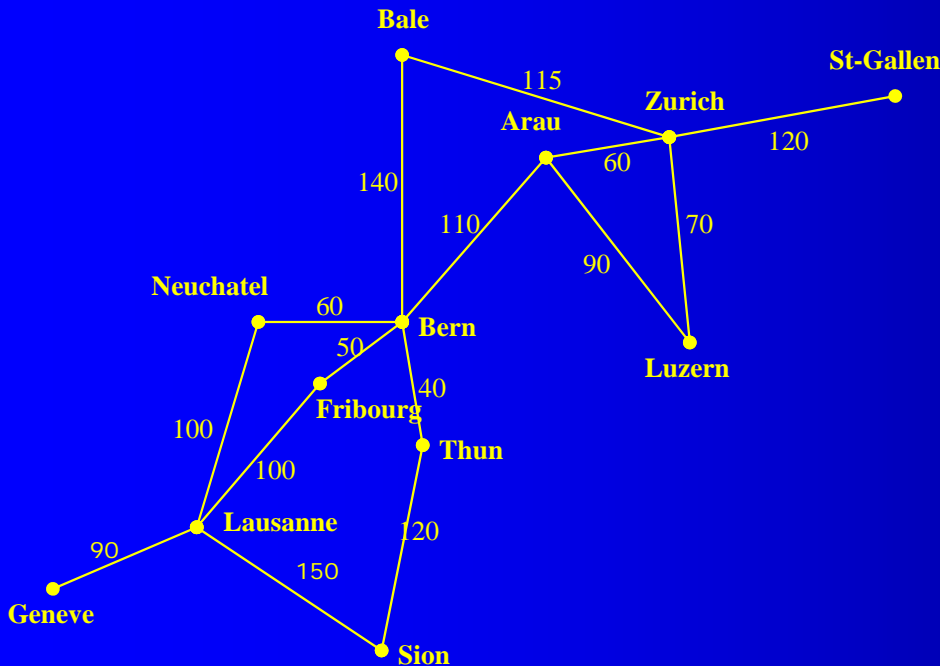
Suboptimal solution, but how bad?

# Evaluating Mechanisms

Methodology: evaluate average performance on randomly generated problem instances

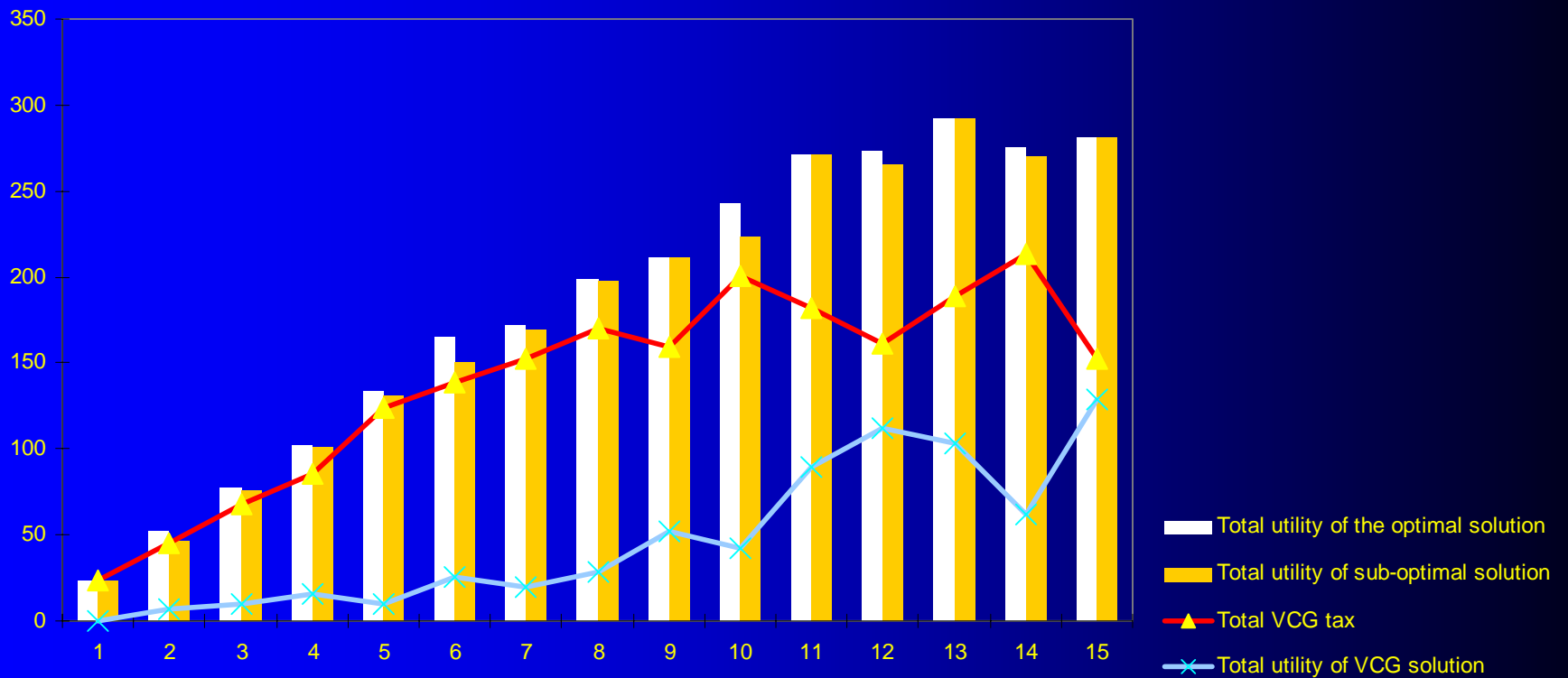
- Structured: model a real-world scenario
- Unstructured: completely random

# Resource allocation in networks



- Agents have different tasks and utilities
- Task = connect 2 nodes in graph
- Each link can only be used for one task  
=> Allocate tasks to maximize revenue

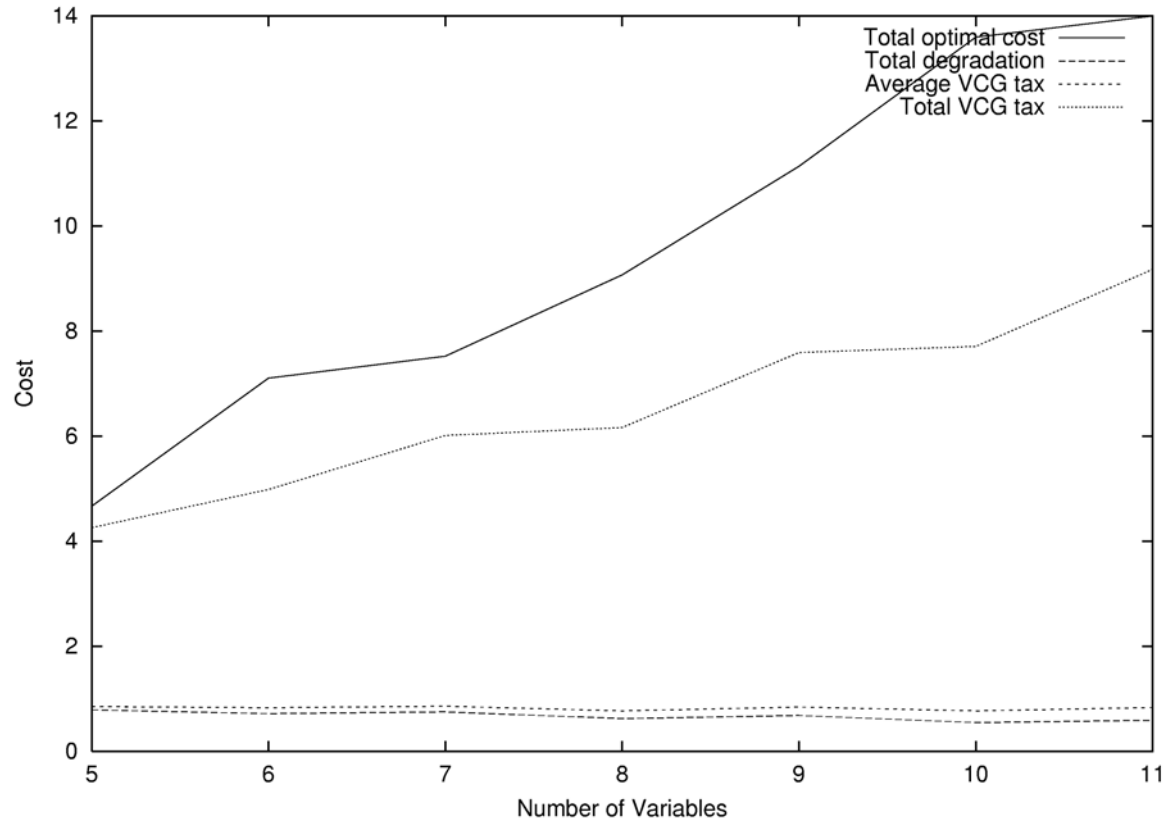
# Revenue-free vs. VCG



# Unstructured problems

- Randomly generate set of variables, choices and constraints
- Relations = random value for each combination, uniformly distributed in  $[0..1]$ , model cost
- Each agent seeks to minimize sum of its relations

# Random Problems



# A problem...

One agent excluded everywhere  
=> one airline gets no slots...

Solution:

- break relations into  $o$  subsets  $R^1, \dots, R^o$   
(orthogonal to agents)
- choose excluded agent  $A_{e(j)}$  separately  
for each subset  $R^j$
- optimize for  $\bigcup_{j=1..o} R^j \setminus R^j_{e(j)}$

# Distributing Exclusions

Tax = *average* tax if one agent ( $A_e$ ) were excluded everywhere:

$$\text{Pay}(A_i \rightarrow A_e) =$$

$$\frac{1}{k} \sum_{j \neq i, e} R_j(V_{R \setminus (R_i \cup R_e)}^*) - R_j(V_{R \setminus R_e}^*)$$

$$\text{Pay}(A_e \rightarrow A_i) =$$

$$\frac{1}{k} \sum_{j \neq i, e} R_j(V_{R \setminus (R_i \cup R_e)}^*) - R_j(V_{R \setminus R_i}^*)$$

$$\text{Pay}(A_i) =$$

$$\frac{1}{k} \sum_{e \neq i} \sum_{j \neq i, e} R_j(V_{R \setminus R_i}^*) - R_j(V_{R \setminus R_e}^*)$$

# Distributing Exclusions

Relations have same distribution:

- expected influence identical for all agents
- to  $A_i$ , irrelevant whether  $A_j$  or  $A_l$  is excluded

=> For risk-neutral agents,  
mechanism remains individually  
rational and incentive-compatible

# Generalizations

“Social compromise” (analogous to reverse auction):

- can be made IR/IC ex-post for risk-neutral agents

Double auctions:

- Can be made IR/IC ex-interim (in expectation) for risk-neutral agents

# Implementation

- Required: optimization algorithm
- Centralized: integer programming, constraint programming
- Distributed: distributed constraint optimization
- Utility elicitation  
=> open constraint programming  
[Faltings and Macho-Gonzalez]

# The future is bright...

- Agents allow complex protocols for efficient social choice
- Revenue-free mechanisms can align incentives for *all* participants
- => possible to greatly improve efficiency in many social choice problems

# The Real "New Economy"

- Increasing population means increasing contention of resources
- = > increasing need for social choice
- Traditional protocols are inefficient
  - Market mechanisms create wrong incentives
  - Agent-based systems can implement new decision mechanisms that provide the right incentives to everyone

