Economic Mechanisms for Allocating Network Bandwidth

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Topics for Today

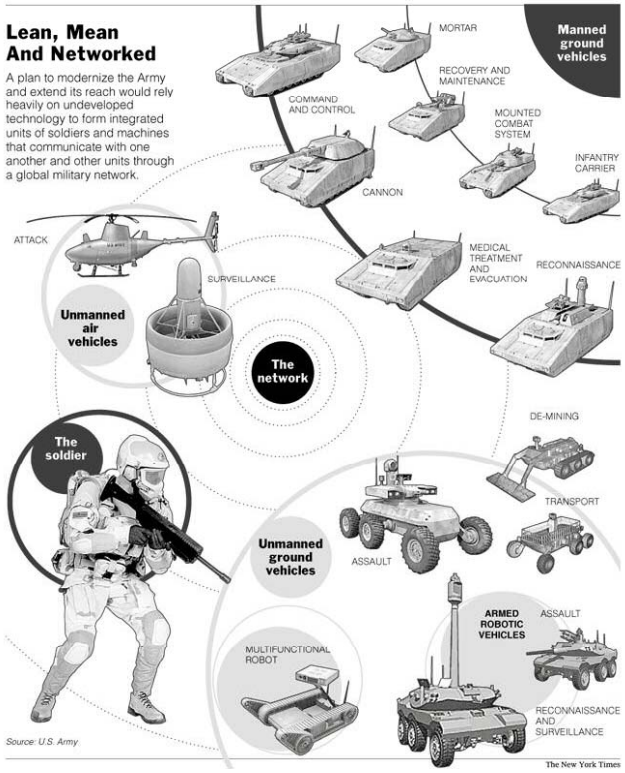
- Markets for scarce computational resources
- Selected details on mechanism design
- Economic mechanisms for allocating tactical network bandwidth
- The road to mechanism engineering

Characteristics of Scale in Net-Centric Systems

Network-centric systems have

- unbounded number of computational agents and human agents
- operating in a decentralized and autonomous fashion
- in an environment with complex, possibly dynamic network topology
- while seeking diverse and possibly competing individual goals
- *and where there is a desired global system state or outcome*

Systems solutions that rely on central control or a complete central picture of global system state are not workable.



Resource Allocation is an Example

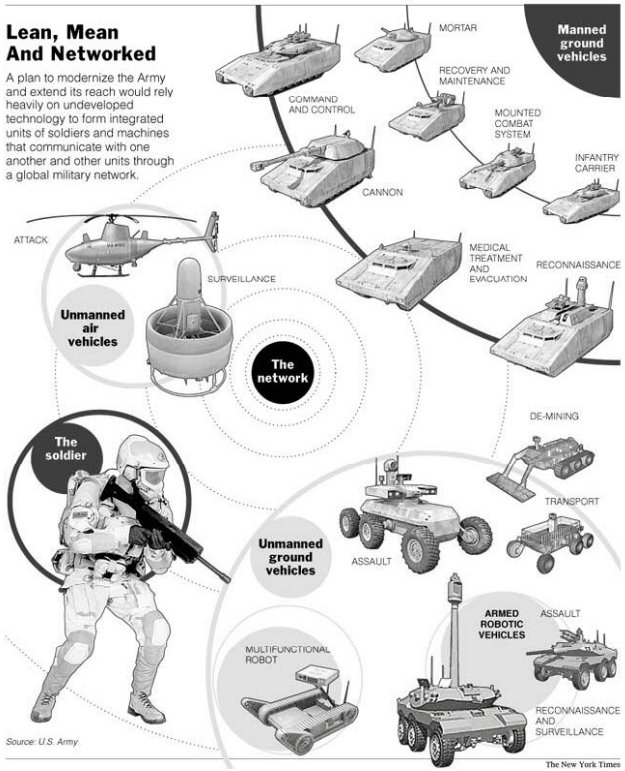
Tactical network bandwidth is a scarce resource

> "*When the supply of bandwidth becomes inadequate during combat, military operations officers have sometimes been forced to subjectively prioritize the transmission of messages. They do this by literally pulling the plug temporarily on some radio or computer switching equipment in order to free up enough bandwidth*"[1]

Allocating scarce resources is economics

- Central allocation = command economy

Can we use market mechanisms to allocate bandwidth?



1. Excerpted from The Army's Future Combat System (FCS): Background and Issues for Congress, Congressional Research Service, RL32888.

What Is Mechanism Design?

Mechanism design concerns

- designing institutions (or protocols) …
- that govern the interactions …
- of rational individuals with …
- private preferences …
- in a way that leads to a collective decision …
- that satisfies a prescribed global criteria.

Examples:

- Voting: Citizens of a community cast yes/no ballots to collectively decide whether to spend municipality funds on a community project.
- Auction: Individuals bid for goods and goods are allocated to bidders
- Markets: Buyers, sellers determine clearing value of goods

Mechanism Design

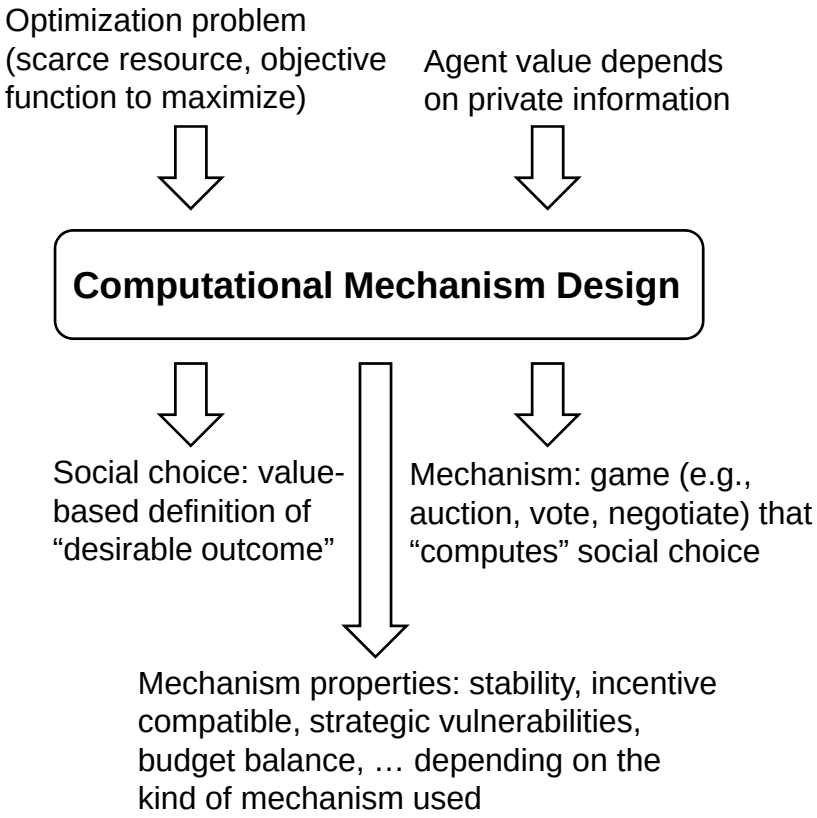
MD uses economics and game theory to model and accommodate *rational* and *intelligent* behavior…

- so that desired global effect is an equilibria of "selfish" behavior

Each agent has private information needed to compute solutions…

- and the mechanism elicits truthful information ("incentive compatible")

Note: Not easy to do, but there are many mechanism design examples



A Few Interesting Facts…

98%+ of Google's $6.7B revenue in 2006 derived from their keyword auction mechanism – but they did not get it right the first time!

FCC has auctioned licenses for electromagnetic spectrum since 1994; the rules are meticulously designed and quite complex

- see http://wireless.fcc.gov/auctions/default.htm?job=papers_studies

In 2007 three Nobel prizes in economics for mechanism design:

Leonid Hurwicz Aug. 21, 1917 - June 24, 2008

[Hurwicz] "worked to rebuild economic theory from the ground up based on a view that what markets do is communicate information ... that incentives to communicate were what we needed to study, under any system"

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Consider Auctions

Most people would be surprised by the variety and complexity of auctions, but the following gives a good intuition of what mechanisms are all about.

An auction is a mechanism[1]:

- Rules: How and when do bidders (agents) make their bids?
- Private information: How much does the bidder value an item up for bid?
- Self interest: Bidders seek to maximize their "payoff" from the auction
  - Payoff = Bidder's True Value – Bidder Payment, more formally $u = v - t$
- Bidder strategy: maybe misrepresenting their true value is most profitable?
  - Why pay full price if you don't have to?
- Efficient Allocation: Item up for bid goes to the bidder with highest true value

1. *Adopted from Varian, "Economic Mechanism Design for Computerized Agents"*

Several Familiar (And Not So Familiar?) Auctions

The mechanism designer must

- Design the rules of the auction
- To achieve the desired result
- By inducing an “incentive compatible” bidding strategy

Key Idea:

- Rules and strategies determine what social choice (results) are achieved
- They also determine the overhead of the solution, and other qualities

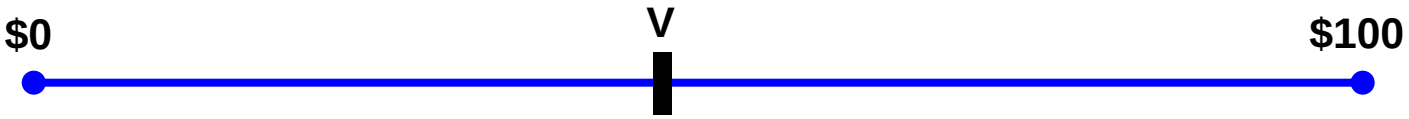
Auction 1:
- Rules: First-price, open-cry
- Strategy: Bid reflects value
- Results: Maximizes total value
- Overhead: High

Auction 2:
- Rules: First-price, sealed-bid
- Strategy: Bidders might lie
- Results: Value maximization not guaranteed
- Overhead: Low

Auction 3 (Vickrey):
- Rules: Second-price, sealed-bid
- Strategy: Bid reflects value
- Results: Maximizes total value
- Overhead: Low

Truthful Bidding in the Vickrey Auction: Proof

Let's say you have value V = 50 for an item



What value B should you bid for an item?

Key intuition: in the Vickrey, payment does not depend on what you bid

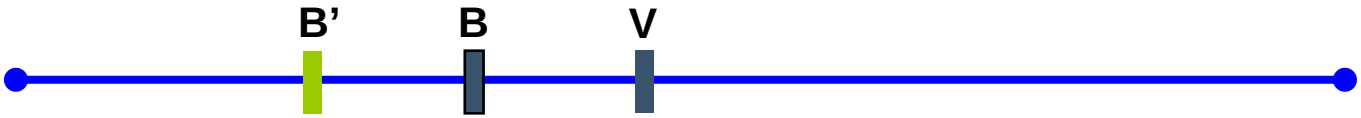
Consider all possible bids B' from a competing bidder

1. *Adopted from Varian, "Economic Mechanism Design for Computerized Agents"*

Why Underbidding is Not a Good Strategy

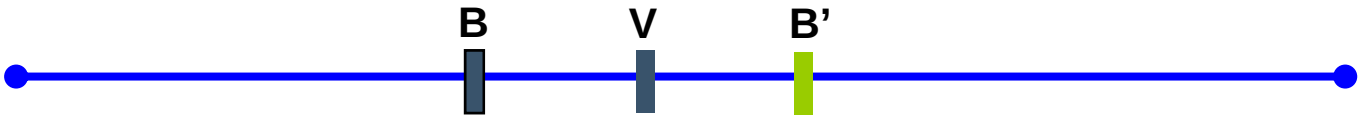
Case 1: B' < B < V 

- You win and pay less than your true value, and that is good for you



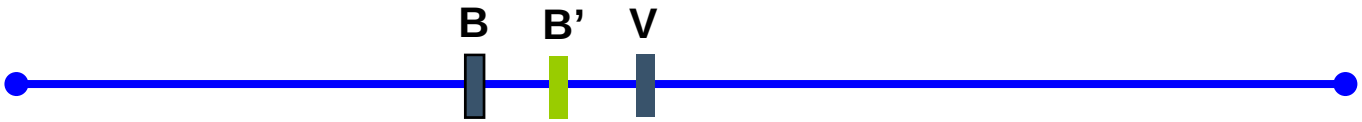
Case 2: B < V < B' 

- You don't win but your competitor apparently valued the item more than you



Case 3: B < B' < V 

- Your competitor won the item for less than your value – you were robbed!



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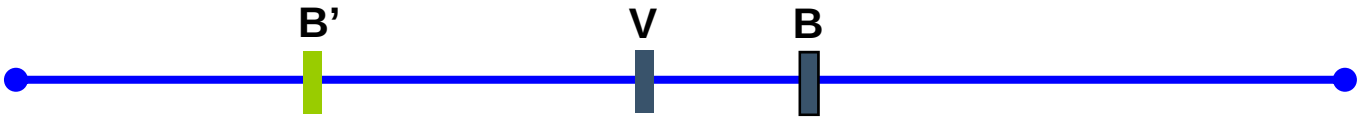

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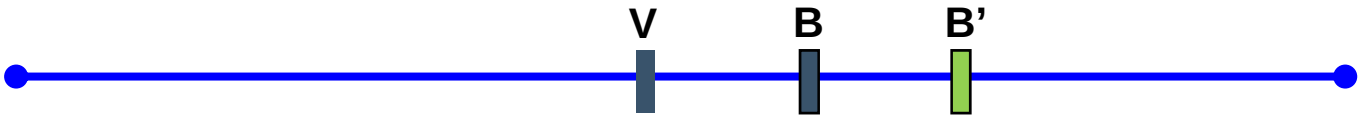

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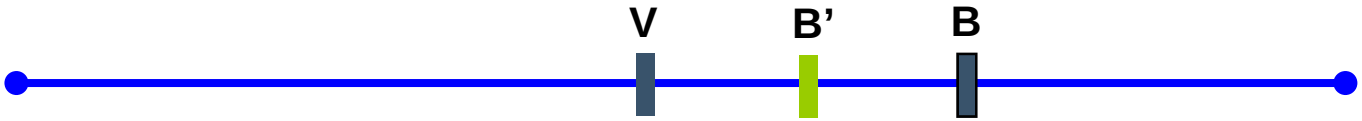

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Vickrey Payment Scheme for Resource Allocation

Network-centric systems resource management will

- allocate resources for changing agent needs and values
- accommodates agents that may be seeking competing goals
- achieve prescribed system goals by virtue of selfish agent behavior

Recall that each agent i wants to maximize their payoff

$$u_i = v_i - t_i$$

Each agent is rational: utility maximizer

Each agent has intrinsic value for an outcome

The art of mechanism design is to find payments…

$$\max \sum_i v_i$$

…so that the social choice (in this example) maximizes the overall value that agent obtains from tactical data.

The Setting: LINK-11

Allocate bandwidth to improve the common operating picture (COP)

- the question is: which track data should be sent on the link?

To answer this need each platform must reveal “private information”

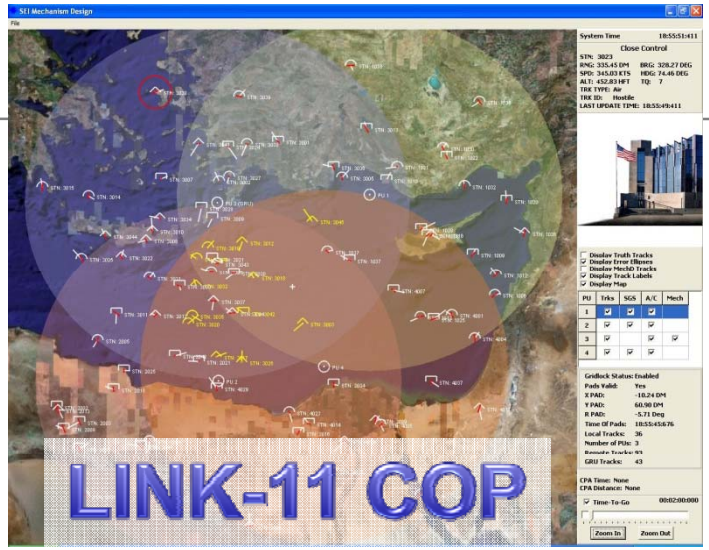
- each platforms knows what tracks it sees and the track quality

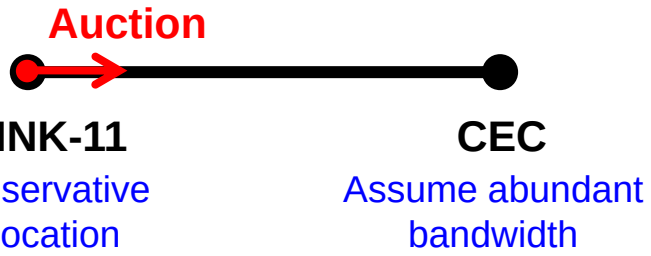
Could a platform behave strategically?

- under-representing track quality might be beneficial to the platform

What mechanism is appropriate?

- VCG auction makes truthful reporting of track quality the best platform strategy





LINK-11 Bandwidth Auction: Summary

Mechanism Design Parameter	Mapping to LINK-11
Resource being auctioned	Track data (bandwidth)
Auction participants	Platforms (ships)
Optimization objective	Improve common operating picture
Private information	Track quality (based on covariance)
Platform value for bandwidth	More data ➔ Better operating picture
Social choice	Maximize overall platform utility
Auction rules	Single-shot, sealed-bid, VCG payment
Currency	Utility is a function of noise/accuracy i.e., information gain is “coin of the realm”
Source of value	Each platform’s contribution to improved COP is “cashed in” after action

Another Setting: Cursor On Target Auctions

Allocate bandwidth in ad hoc tactical net

- UAV video, biometric, position, …
- operators play different roles, have different needs, ideas about “value”
- which operator gets data; at what quality?

Operators have “private information”

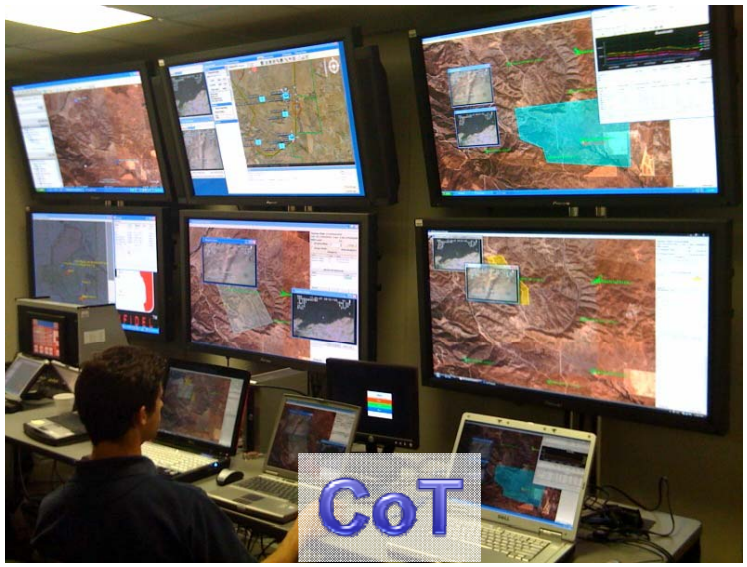
- operators know their local situation, and their role-based value for information

Can an operator act strategically?

- misstating value might get the operator more or better quality data

What mechanism is appropriate?

- we are investigating supply chains and mechanisms that do not rely on “money”



Developed in conjunction with Center for Network Innovation and Experimentation (CENETIX) Tactical Network Topology Experiments at Camp Roberts at California, sponsored by US Special Operations Command (USSOCOM).

LINK-11 & CoT Mechanism – Comparison

Link-11 Tactical Data Network	Cursor-On-Target
Homogeneous collection of agents	Heterogeneous collection of agents
Single type of data	Multiple types of data
Value expressed as single number	Value is situation specific and expressed via doctrine language
Homogeneous value functions: depends on covariance	Heterogeneous value functions: depends on agent task, data type and situation
Broadcast	Unicast
“Supply chains” of length one	Supply chain of arbitrary length
Single “level” of intrinsic value	Two “levels” (commander and agents) of intrinsic value

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Real and Increasingly Important Problem

Computational mechanism design addresses a real problem seen today, and is increasingly important as systems scale in size and complexity

- A system has scarce resources and a need for optimal allocation
- The users of the system have an interest in resource allocation decisions
- Optimization depends on users' private information (users affect allocation)

The above three conditions are needed to consider mechanism design

- Without special circumstances, users *will* behave strategically
- Strategic behavior: a combination of self-interest and guile
- Special circumstances:
  - *real and compelling* social norms that reward *cooperative* behavior
  - an *incentive compatible mechanism* that defines a *user's best strategy*

Mechanism Design v. Mechanism Engineering

Engineering techniques are those that have been made routine:

- They reliably yield predictable solutions for a significant class of problems
- They are documented and (publically) available to practitioners
- They are usable with a reasonable amount of training and experience

Mechanism design is promising, but it has not yet been made “routine”

- Deep foundations (game theory, economics, algorithmic complexity, optimization) is exposed throughout the mechanism design process
  - these foundations interact with one another in the design process
  - practitioners are likely to be unfamiliar with all of these foundations
- Computational mechanisms have been used, but also has active research
  - seemingly “minor” differences in design problems lead to simple mechanism solutions or wide-open research questions.

A Discipline of Mechanism Engineering

We think mechanism engineering is inevitable and is ready to emerge

- Substantial work is needed, we are making progress

We need to document design schemas and patterns

- What DoD problems are best suited to auctions? supply chains? voting? negotiation? What measures of merit are entailed in each of these?

We must integrate mechanism design with other design considerations

- How does mechanism engineering interact with safety engineering, security engineering, performance engineering, requirements engineering?

We must build a practitioner community

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Thank You!

Questions?