

Auction mechanisms for Network Resource Allocation

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This presentation

- Brief **Primer** of Auction Mechanisms
 1. Outline structure of basic auction models
 2. Give flavor of more composite models
 - Sponsored search auctions in internet ads
 - Issues arising in spectrum sharing in cognitive radio networks
 3. Delineate main trends and brainstorm in future challenges
 - Advanced auction models that capture multi-level interaction of entities
 - Double auctions for multiple seller – buyer interaction
 - Decentralized negotiation / resource trading mechanisms

Future Networks

- Future networks: **diverse interacting rational** entities with natural inclination to solicit own objectives
 - Misreporting of utilities, declaration of higher needs, selfishness, abstaining from contributing resources to network, ...
- Need for **decentralized** network control
 - Self-management, autonomous resource trading, ...
- Match **unpredictable supply and demand** profiles
 - Varying spatiotemporal patterns, volatility, intermittent availability
 - Need for online resource sharing, flexible allocation of resources
- Control decisions to be taken under **partial** or **no knowledge** of network state
 - Cost for obtaining feedback
 - Rapid topology / load changes, interference
 - Perfect state may be infeasible or meaningless to have

Future Networks (cont.)

- Internet architecture: **federation** of elements coming into spontaneous interaction
- Recent **regulatory** developments (e.g. spectrum liberalization) in favor of ad-hoc interaction, impose market point of view in resource allocation
- Each entity possesses an amount of resource:
 - Resources brought to common pool, from where a resource allocation regime has to emerge
 - Different twists, depending on resource

Various network instances

- **Wireless ad-hoc:**
 - Forward (own or others') data to next hop with limited Energy and/or Bandwidth
 - Enforce cooperation regime such that total cost is minimized
- **Interference-limited links:**
 - Allocate transmit power
 - Maximize sum of coupled (due to interference) utilities
- **Peer-to-peer:**
 - Peer access link bandwidth shared between upstream / downstream
 - Achieve socially optimal operating point (sum utility maximization)
- **Disruption tolerant (intermittently connected):**
 - Store content in cases of no connectivity, forward if allowed to
 - Allocate cache memory or disk space to sporadic requests and own content)
 - Maximize utility or minimize delay in end-to-end data transfer

Various network instances (cont.)

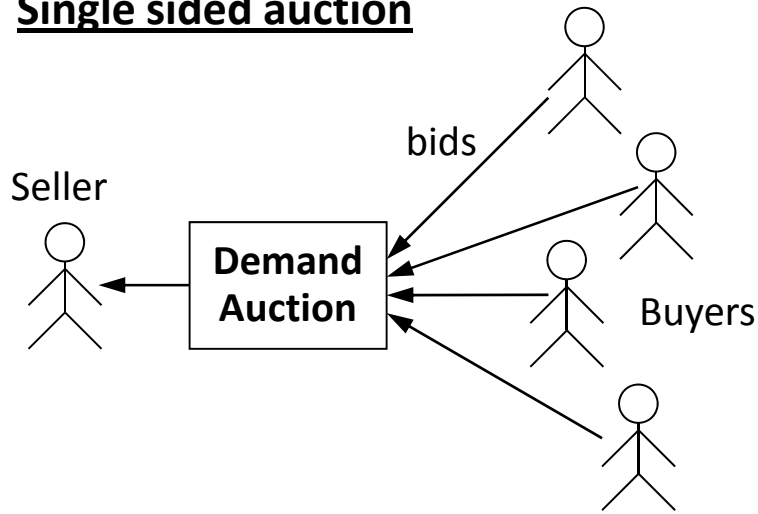
- **Cognitive radio:**
 - Portions of spectrum chunks to be allocated among primary / secondary providers and / or users
 - Maximize revenue of providers, optimize spectrum utilization (reach socially optimal allocation)
- **Virtualized server configurations:**
 - Bottleneck resource : CPU
 - Migrate application processes from machines they actually run on to virtual machines
- **Decentralized data centers:**
 - Data center storage space shared among competing agents
 - Minimize retrieval delay, data transfer delay

Auctions

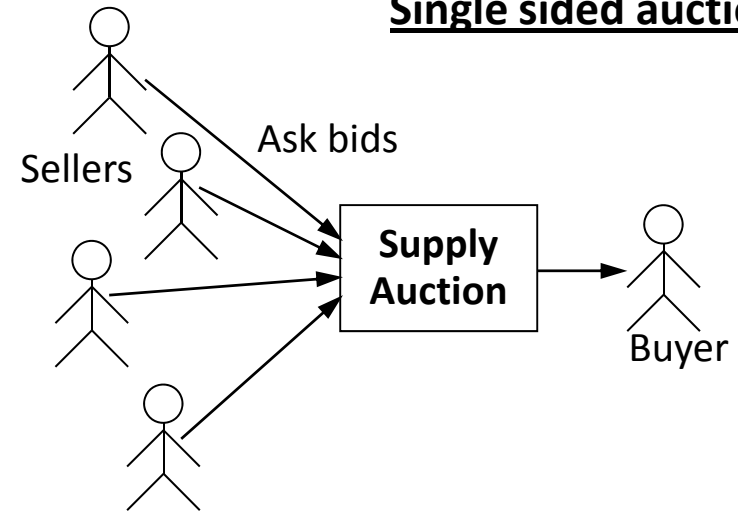
- Auction instances (to sell)
 - One indivisible item to be allocated to one among several buyers
 - Multiple indivisible items to be allocated to buyers
 - Divisible good of quantity C to be allocated among buyers
- Each buyer characterized by utility function (valuation)
- Most common objectives
 - maximize auctioneer revenue
 - maximize allocation efficiency (social welfare)
- Main attractive feature: achieve desired resource allocation **while agnostic to** utility functions
 - limited / distorted state information
 - varying demand / supply
 - diverse, conflicting user interests
 - utility function cannot be precisely captured / determined

Basic Auction Types

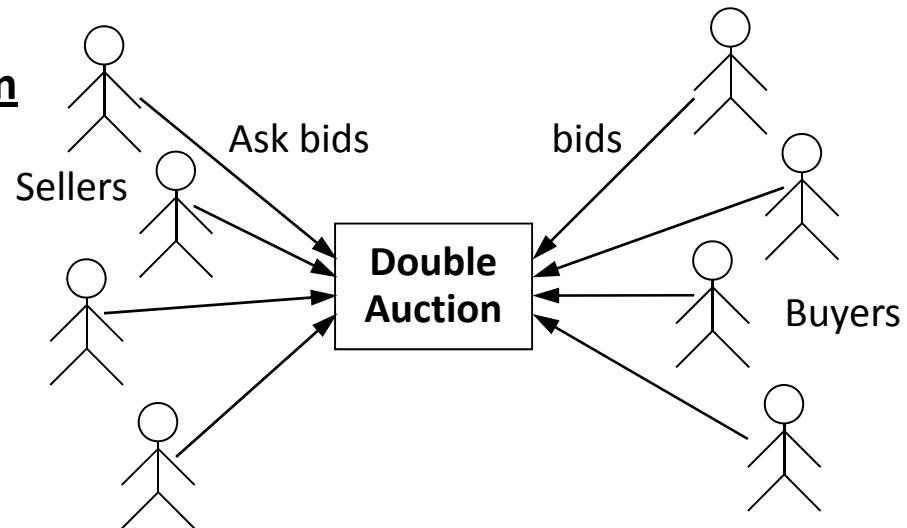
Single sided auction



Single sided auction



Double sided auction



More on basic auction structure

- Good to be allocated to multiple buyers
- Each buyer characterized by a utility (valuation) function, not known to auctioneer and to other buyers
 - satisfaction as function of quantity of good (good divisible)
 - satisfaction from obtaining item (good indivisible)
- Buyers submit bids to auctioneer
- Auctioneer maps bid vector \mathbf{b} to vector \mathbf{x} of allocated quantities and vector of payments \mathbf{p} for each user
- Objectives of resource allocation:
 - maximize social welfare (sum of utilities)
 - Maximize revenue

More on auction design objectives

- A. Maximize incurred **revenue** for seller
 - Increase competition, induce bidders to participate, bid high
 - Increase expected price at which item is sold
- B. Maximize **Efficiency** of allocation
 - 1 item: allocate it to bidder who values it most
 - Multiple indivisible goods or divisible good: maximize social welfare
- A, B may be conflicting
- C. Fairness: w.r.t. to properties of utility vector
- D. Promotion of truthful reporting of valuations
- E. Discouragement of collusion
- F. Simplicity of mechanism, ...

Single-item auctions

- A seller to allocate an indivisible item to one out of N buyers
- Each buyer i knows only own valuation u_i of item, auctioneer knows none of valuations (private value auction model)
- Class of Open-type auctions
- **Ascending price (English):**
 - Auctioneer starts by announcing a low price, keeps increasing it as long as there exist at least two interested parties
 - (Or bidders may bid higher and higher)
 - Auction stops if *one* interested bidder remains
 - That last bidder obtains item, pays amount equal to *price at which second-last bidder dropped out*
- **Descending price (Dutch):**
 - Auctioneer starts by announcing a high price, keeps decreasing it until the first bidder declares interest at that price
 - That bidder takes item, pays amount *equal to that price*

Single-item Auctions (cont.)

- Class of Sealed-bid auctions
- **Sealed-bid first-price auction**
 - Bidders submit bids in *sealed* envelopes
 - Bidder with *highest* bid wins item, pays amount he bid
- **Sealed-bid second-price auction (Vickrey)**
 - Same, but highest bidder pays *second-highest* bid
 - Truthful declaration of valuation: no incentive not to bid true valuation
 - For any configuration of competing bids, bidder either loses in net payoff or does not gain anything from bidding $b_i \neq u_i$
- Under private value model:
- **Open Dutch auction** equivalent to **Sealed-bid first price auction**
- **Open English auction** equivalent to **Vickrey auction**

Risk Averseness vs. Risk-neutrality

- Risk-averseness (neutrality) -> concave (linear) utility function
- Risk-averse seller
- Say auction runs many times, item sold at price p_i at i -th time
- $E_p[U(P)] \leq U(E[P])$
 - Average utility from repeating auction (with different payments) less than utility at average payment
 - Payment variability around mean reduces utility
 - Seller prefers auction with more balanced payments, even if this leads to smaller average payments
- Risk-averse bidder
- Similar definition, for average net benefit (average over bidding)
- Risk-neutrality
 - Variability around mean does not reduce utility
- Expected seller revenue (expected payment) is the same for first- and second-price auctions (Revenue Equivalence principle)

More Taxonomy

- **Private** valuations: bidder knows only its own valuation
 - If a statistical model used, bidder knows probability distribution of own valuation and of others
 - Knowledge about others' valuations does not affect own
- **Interdependent** valuations: bidder has full or partial information about own valuation
 - Its valuation affected by information available from others
- **Multi-object auctions**
- **Homogeneous** (multi-unit) vs. **heterogeneous**
 - Homogeneous: **uniform-price** / **discriminatory-price**
- **Sequential** vs. **simultaneous**
- **Individual** vs. **combinatorial**

Auction mechanisms for **Divisible** resources

- Divisible good C to be allocated to N users
- User i : utility function $U_i(x)$
- Social Welfare Maximization problem (SWM)

$$\max_{x \geq 0} \sum_{i=1}^N U_i(x_i)$$

subject to:

$$\sum_{i=1}^N x_i = C.$$

- If utility functions were known by controller:
 - SWM solution: x_i^* is such that: $U'_i(x_i^*) = \lambda$, $x_i^* > 0$, and $U'_i(0) \leq \lambda$.
- Challenge: controller does not know utility functions, aims at socially optimal allocation
- Class of allocation mechanisms where each user submits bid b_i for amount he is willing to pay, and charged according to function $c(\cdot)$
- Allocated amount: $x_i(b_i) = b_i / \lambda$: λ price per unit of resource

Kelly mechanism

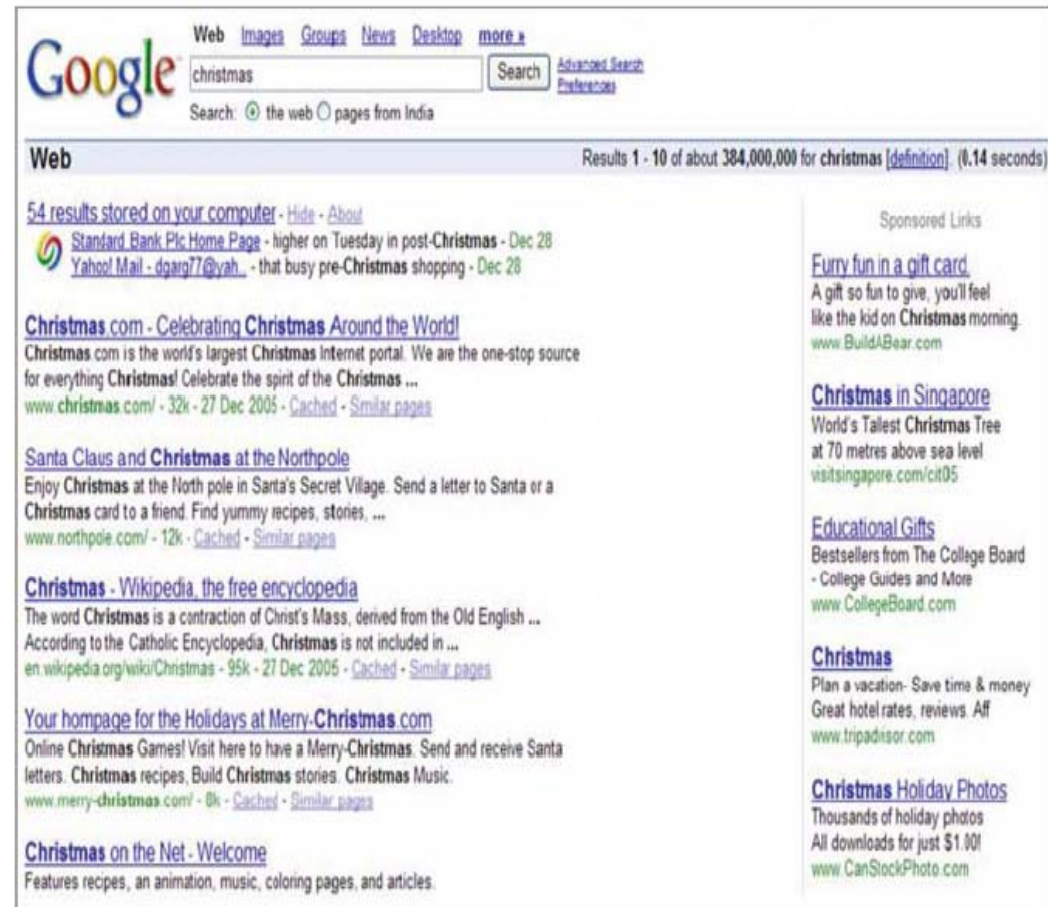
- Price-taking users: **not** anticipate impact of bid on price (charge function)
- Rational bidders: cast bid to maximize net benefit: $U_i(x_i(b_i)) - c(b_i)$
- Say, given the bids, auctioneer solves problem (P):
- $\max_x \sum b_i \log x_i$ s.t $\sum x_i = C$ (P)
- Turns out that if charge function is $c(b) = b$, **solutions of problems (P), (SWP) coincide**
 - so are Lagrange multipliers (equal to $\sum_i b_i / C$)
 - Proportional allocation optimal: $x_i = b_i C / \sum_i b_i$
- Kelly ('98): Iterative decentralized approach
 - Market price computed by auctioneer from dual problem (increases or decreases it, based on bid demand)
 - Users adjust bids based on price
- Price-taking users: one-dim bidding and appropriate charging **suffice** for socially optimal allocation

VCG Mechanism

- Price-anticipating users: strategically adapt bid, consider impact on price
- Efficient (socially optimal) allocation : VCG mechanism
- Bidders requested to reveal utility functions $U_i(.)$
- User i bid is a function $b_i(x)$ of amount of resource x
- Amount charged to each user: externality caused to others
 - Total utility reduction caused by presence of i to all others
- Desirable properties
 - Efficiency of allocation
 - Truthful reporting of utility is best for each user
 - *Undesirable: huge complexity
- VCG-Kelly type mechanisms proposed (Hajek, Johari, Tsitsiklis)
 - 1-dim bids, proportional allocation, charging as in VCG
 - Efficient allocation, but lose property of truthful utility reporting

Sponsored Search Auctions: internet ads

- Auctioneer: search engine
- Bidders: advertisers, wishing to have their ad appear on user's search screen after search
- Ads appear in ranked list
- User clicks on ad and is taken to respective site
 - Advertiser pays search engine for that
 - Each time a user clicks on an ad
- Ad positions (rank slots) are auctioned
 - The higher the rank of an ad, the more probable that ad will be clicked on by a user



The screenshot shows a Google search for 'christmas'. The search bar contains 'christmas' and the search button is visible. Below the search bar, there are navigation links for 'Web', 'Images', 'Groups', 'News', 'Desktop', and 'more'. The search results are displayed in a list format. The first result is 'Standard Bank Plc Home Page - higher on Tuesday in post-Christmas - Dec 28'. The second result is 'Yahoo! Mail - dgarg77@yah. - that busy pre-Christmas shopping - Dec 28'. The third result is 'Christmas.com - Celebrating Christmas Around the World!'. The fourth result is 'Santa Claus and Christmas at the Northpole'. The fifth result is 'Christmas - Wikipedia, the free encyclopedia'. The sixth result is 'Your homepage for the Holidays at Merry-Christmas.com'. The seventh result is 'Christmas on the Net - Welcome'. On the right side of the page, there is a 'Sponsored Links' section with four ads: 'Furry fun in a gift card', 'Christmas in Singapore', 'Educational Gifts', and 'Christmas Holiday Photos'.

Sponsored Search Auctions (cont.)

- Ad auctions: auctioneer revenue / bidder payoff depend on internet user satisfaction
- N advertisers bid for $K < N$ ad positions
- b_i : bid per click of advertiser i
- CTR_{ij} : probability that i 's ad clicked when in position j (obtained through historical data)
- $CTR_i = \sum_j CTR_{ij} \times \text{Prob}(\text{ad } i \text{ displayed in position } j)$
- AUCTION
- Advertisers bid b_i
- Google makes ad appear in slots in decreasing order of $b_i \times CTR_i$
- Advertiser in k -th position with $b_{(k)} \times CTR_{(k)}$ pays $b_{(k+1)} \times CTR_{(k+1)}$
- Payment per click: $p_{(k)} = b_{(k+1)} \times CTR_{(k+1)} / CTR_{(k)}$
- Known as **Generalized Second Price (GSP) auction**

Spectrum auctions

- Dynamic spectrum access / spectrum sharing
- Licensed spectrum bands of Primary Operator (PO)
- Coordinate unused spectrum leasing to Secondary operators (SOs)
 - SO: local one, smaller range operator
 - SOs further allocate spectrum to secondary users
- Utility derived difficult to estimate
 - Depends on unpredictable demands, availability, channel quality, geographical range of SOs, interference, channel sensing inaccuracies, ...
- Spectrum reuse by operators or users at far away locations
 - Interference restricts set of feasible channel allocations
- Spectrum bands differ in quality (reuse, fading, freq. selectivity)
- Heterogeneity, unpredictability of demands, mobility
- Online fashion of allocation

Future Direction 1: Advanced Auction Models

- Example: **Multi-tier** model
- **Primary Operator** → **Secondary Operator** → **Secondary User**
- Are conventional auction models sufficient?
 - SOs bid, PO decides allocation + payment, done
 - Probably not...
- Appropriateness of frequency allocation from PO to SO depends on experience of secondary user, served by SO
- Not good for a PO to allocate a frequency to SO that will allocate it to a user for which frequency is of low quality (due to interference, limited SO range)
 - End users served by SO most likely are clients of PO as well!

Future Direction 1: Advanced Auction Models (cont.)

- **Primary Operator** → **Secondary Operator** → **Secondary User**
- Consider feedback from **end-user (secondary user) substrate** (besides PO valuations)
- Spectrum allocation : modulate SO bid with end-user (secondary user) experience
- End-users satisfied and willing to use PO for other services
- PO benefits as users choose him and not other POs
- **Connection with sponsored auctions in internet ads?**
 - Ongoing work towards this direction

Future Direction 2: Double Auctions

- Each entity possesses resource, engages in transactions
 - Different needs, different utilities
- Resource exchange in market style among resource **providers** and **consumers**
- Providers with excess spectrum (or other resource) may sell to other providers in need of resource

- Bird's eye view: match spatiotemporally varying demand and supply patterns
- Microscopically: double auctions
- Buyers contend to obtain resources by placing bids to several sellers
- Sellers announce ask bids at which they sell
 - Multi-lateral transactions

Future Direction 2: Double Auctions (cont.)

- Multiplex supply and demand in space and time to achieve best resource utilization
- Derive allocation and payment rules for selling and buying resources
- Multiple sellers and buyers: objective ?
 - Maximize revenue for all would lead to tragedy of commons
 - Various properties of network operating points
- Resource reciprocity mechanisms
- Interdependent resource provider and consumer role
 - E.g. in peer-to-peer networks, link capacity used either for download or for upload
 - Client role places restrictions to the other (server) role!
 - Ongoing work: substitute role of auctioneer with distributed approach

Future Direction 3: Negotiation and Trading

- **Negotiation** among different entities
 - cooperative entities that accept to negotiate
 - entities have conflicting interests
- Goal: reach mutually desirable allocation regime
- An entity attempts to affect outcome by making offers to others
 - Other parties may accept offer, reject offer or make alternative ones
- Issue: available information at an entity about other entity
- A framework for negotiation and resource trading for networks?